Pirooz Azad, S., Leterme, W. and Van Hertem, D., “Fast breaker failure backup protection for HVDC grids,” Electric Power Systems Research, Special Issue: Papers from the 11th International Conference on Power Systems Transients (IPST), vol. 138, pp. 99–105, Jun. 2016.

Digital Objective Identifier: [doi:10.1016/j.epsr.2016.03.003](https://doi.org/10.1016/j.epsr.2016.03.003)

URL: <http://www.sciencedirect.com/science/article/pii/S0378779616300505>

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Fast Breaker Failure Backup Protection for HVDC Grids[☆]

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Abstract

High voltage direct current (HVDC) grid protection must clear dc faults within a time-frame of milliseconds to avoid damages to power electronic components due to fast rising dc fault currents. If the breaker associated with the primary protection fails, backup must be provided to clear the faults which would otherwise persist. Backup relaying algorithms originally developed for ac systems delay the detection of primary protection failure until the expected primary fault clearance instant. Application of similar algorithms to HVDC grids results in a long fault clearing time, which requires converters and breakers to withstand unrealistically large currents. To reduce the fault clearing time, this paper proposes two fast backup relaying algorithms which detect local and remote breaker failure before the expected primary fault clearance instant. The proposed algorithms use thresholds on the voltage and current measurements to detect breaker failure. They are evaluated using a four-terminal HVDC grid test system implemented in PSCAD.

[☆]This paper was submitted to “Special issue based on selected expanded contributions from the 11th International Conference on Power System Transients (IPST)”

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The study results show that the proposed algorithms can reliably detect breaker failure within few milliseconds after fault inception. Furthermore, the algorithms provide faster backup protection compared to methods based on ac backup protection philosophy. The resulting decreased fault clearance time reduces the maximum dc fault current and consequently, leads to lower required ratings for HVDC grid equipment.

Keywords: backup protection, breaker failure, HVDC grid, power system protection, VSC HVDC

1. Introduction

Voltage source converter (VSC) high voltage direct current (HVDC) systems are expected to play an important part in the future European electricity system [1]. Beside point-to-point connections, VSC HVDC grids are considered to efficiently integrate renewable energy sources and to facilitate a pan-European energy market. An essential feature of a reliable HVDC grid is protection against short-circuit faults on dc lines or buses. The main challenge for HVDC grid protection is the required high operation speed, as dc fault currents quickly increase to high steady-state values [2]. These currents should be interrupted fast enough to avoid damages to the power electronic components. HVDC grid protection must operate one order of magnitude faster than its ac counterpart [3].

Various algorithms have been proposed for fast and selective HVDC grid primary protection [4, 5, 6, 7]. These algorithms detect the fault and identify its location within a few milliseconds. To confine the fault impact to the faulted line, a selective fault clearing strategy clears the fault by opening the dc breakers at the two ends of the faulted line [8]. By contrast, non-selective fault clearing

strategies interrupt dc fault currents through combined action of multiple equipments such as converters with fault blocking or fault current limiting capability [9, 10, 11, 12, 13]. For non-selective strategies, dc faults typically affect the entire or a large section of the HVDC grid. As non-selective methods are only effective in small systems, this paper focuses on selective fault clearing algorithms.

For selective HVDC grid protection, backup protection is required in case of primary protection failure. A primary protection failure can be caused by a malfunction of the primary relay, breaker or communication system [14]. In ac systems, the backup protection operation is delayed with respect to the primary protection to allow the latter to initially deal with the fault [15].

A relaying algorithm for backup protection in HVDC grids is proposed in [4]. This algorithm detects primary protection failure if the current through the primary breaker does not become zero at the expected primary clearing instant. The disadvantage of this algorithm is its long fault clearance time [16]. In [17], breaker internal measurements are used to determine primary breaker failure. Although this algorithm is fast, its dependence on internal measurements of the breaker limits its application in multi-vendor HVDC grids.

This paper proposes two fast relaying algorithms for local and remote breaker failure backup protection. The proposed breaker failure backup relaying algorithms distinguish cleared faults from uncleared ones during the fault clearing process of primary protection. Since these algorithms only use primary voltage and current measurements at line ends, their performance is independent of breaker internal characteristics.

The paper is structured as follows: Section 2 presents the HVDC grid test system and its components' models. This section also provides an analysis of the

voltage and current waveforms in the test system after a fault. Section 3 presents the principles of breaker failure backup relaying algorithms. The application of the proposed relaying algorithms to an HVDC grid test system is presented in Section 5. Conclusions are stated in Section 6.

2. HVDC Grid Model and Dc Fault Analysis

2.1. HVDC grid model

The four-terminal HVDC grid test system of [18] was used for the studies of this paper (Fig. 1). In this test system, four half-bridge modular multilevel converters are connected via five cables to form a meshed HVDC grid. A dc breaker is included at the end of each cable. An inductor that limits the rate of rise of the fault current is located in series with each dc breaker. The system parameters and components' models are similar to those of [18], except for the series inductor value which has been reduced to 50 mH. This section briefly presents the model of cables, converters and breakers considered in the transient simulation studies. The simulations were performed in PSCAD.

2.1.1. Cable model

To accurately simulate the high frequency transient waveforms after a dc fault, the cables are represented by the frequency dependent (phasor) cable model. This is a distributed parameter model which takes the frequency dependency of cable parameters into account [19]. The cable used in the studies of this paper has a surge impedance of 33.7Ω and a traveling wave speed of 183.46 km/ms (evaluated at a frequency of 1 MHz).

2.1.2. Converter model

The converters are represented by a continuous model with blocking capability to speed up simulations while providing adequate accuracy [20]. In this model, instead of modeling all individual submodules, each converter arm is represented with a continuous voltage source. The converter's insulated gate bipolar transistors (IGBTs) are blocked if the arm current exceeds 1.6 times the IGBT continuous current. This protects the IGBTs against overcurrents since the maximum instantaneous overcurrent that an IGBT can safely tolerate is around 2 times its continuous current.

2.1.3. Breaker model

Hybrid dc breakers are considered for the studies of this paper. The hybrid breaker is modeled as a switch in parallel with a surge arrester (Fig. 2). After a certain time delay t_{br} from the instant the breaker receives a trip signal, it inserts a countervoltage in the system. The value of the countervoltage is determined by the rating of the parallel surge arrester and is typically 1.5 times the rated dc voltage (480 kV in this case). The time delay t_{br} represents the time required by the dc breaker to open after receiving the trip signal and is assumed to be 2 ms for the considered dc breakers [8].

2.2. Fault analysis

As an example, the waveforms seen by relays R_{13} and R_{31} for a solid pole-to-pole fault in the middle of line L_{13} and a similar fault at bus 1, are analyzed. The waveforms are obtained by voltage and current measurements at the cable side of the breaker inductor. For both faults, two scenarios in which breaker B_{13} clears the fault or fails in removing the fault, are discussed.

Figure 1: Four-terminal HVDC grid test system

Figure 2: Hybrid HVDC breaker model

2.2.1. Pole-to-pole fault at L_{13}

After fault inception, the voltage and currents measured at R_{13} show the successive reflections of the fault wave between the fault location and breaker series inductor (Fig. 3, solid line). The fault occurs at $t = 0$ ms and creates a traveling wave which arrives at the two terminals of L_{13} at $t = 0.54$ ms due to the finite traveling wave speed. The fault wave travels back and forth between the two discontinuities on L_{13} , i.e., series inductor and the fault location, and results in successive reflections at the terminals. In the literature, several algorithms are

proposed for detecting and identifying faults based on these reflections [6, 7, 21].

The voltage and current waveforms for the two scenarios differ after $t = 2.54$ ms, which is equal to the sum of the time required for the wave to travel from the fault location to R_{13} , the fault detection time and breaker opening time (Fig. 3). If B_{13} fails to clear the fault, the voltage measured at the end of the faulted line decreases to a near-zero value, whereas the current increases to a high value. If B_{13} opens at $t_o = 2.54$ ms and clears the fault, the voltage measured at R_{13} increases and returns to its pre-fault value, whereas the current returns to zero. As B_{13} opens, the voltage rises above the nominal value due to series insertion of the surge arrester in the line.

2.2.2. Pole-to-pole fault at bus 1

For a fault at bus 1, at $t = 1.1$ ms, the voltage measured at R_{13} decreases whereas the current increases (Fig. 4). The bus fault gives rise to traveling waves which propagate on the adjacent lines L_{12} , L_{13} and L_{14} towards the remote relays R_{21} , R_{31} and R_{41} . Due to the series inductor located between the fault location and the line end, the steepness of these waves is reduced.

The waveforms for cleared and uncleared faults differ after $t = 3.1$ ms, which is equal to the sum of the traveling time of the wave on L_{13} to reach R_{31} , fault detection time by R_{13} and B_{13} opening time. If the relaying algorithm associated with busbar protection, e.g., the differential algorithm of [22], detects the fault and B_{13} interrupts the fault current, the voltage and current measured at R_{31} increase and decrease, respectively. If B_{13} fails, the voltage remains at a low value whereas the current increases.

Figure 3: Voltage and current at R_{13} for a fault in the middle of L_{13} (solid: uncleared due to breaker B_{13} failure, dashed: cleared by primary protection)

Figure 4: Voltage and current at R_{31} for a fault at bus 1 (solid: uncleared due to breaker B_{13} failure, dashed: cleared by primary protection)

3. Local Breaker Failure Backup Relaying Algorithm

3.1. Overview

The local breaker failure backup relaying algorithm makes use of the voltages and currents measured at the primary relay to detect primary breaker failure

(Fig. 5). Upon detection of a fault at line AB, the primary relay R_{prim}^A sends a trip signal to the breaker located at A and starts a timer which imposes a delay t_{pb} on the operation of the breaker failure backup relay R_{bf}^A . After the delay, R_{bf}^A uses the current and voltage measurements to distinguish a cleared fault from an uncleared one. If R_{bf}^A detects an uncleared fault, it generates a trip signal for the breakers located at C and E to clear the fault.

To prevent backup protective actions before those of the primary protection, the minimum required time delay between primary fault detection and backup action initiation is t_{br} (Fig. 6). In Fig. 6, a fault occurred at t_f is detected by the primary protection system at t_d . If the primary breaker operates properly, the breaker opens at t_o and the fault is cleared by the primary protection system at t_c . In case of breaker failure, the backup protection system detects the uncleared fault at t'_d , trips the adjacent breakers at t'_o and clears the fault at t'_c . The proposed backup relaying algorithm starts detecting uncleared faults after t_o .

The delay between primary fault detection and backup action initiation, t_{pb} , can be adjusted based on the required speed and reliability of HVDC grid protection. A longer delay improves the reliability of the backup relaying algorithm since the separation between samples for cleared and uncleared faults increases. A longer delay also increases the required ratings for grid equipments as they must withstand larger currents due to the longer fault clearance time.

3.2. Principle

Fig. 7 shows the relaying characteristic of the proposed backup protection, as well as a sketch of the loci of voltage and current measurements at a relay for a fault which is cleared or remains uncleared by the primary protection. The arrows indicate the direction of changes in the voltage and current measurements as a

Figure 5: Overview of proposed local and remote breaker failure backup protection systems

Figure 6: Time continuum of fault clearance by primary and breaker failure backup protection

function of time. The pre-fault voltage and current values are indicated by U_0 and I_0 . The voltage and current values at t_o are denoted by (U_o, I_o) . The prospective steady-state current and voltage values associated with the cleared and uncleared faults are indicated by $(U_c, 0)$ and (U_{uc}, I_{uc}) , respectively.

The proposed local backup relaying algorithm detects primary breaker failure by dividing the UI-plane into two regions, i.e., cleared and uncleared faults. The line which divides the plane into two regions depends on both voltage and current measurements. By identifying the region to which the locus of the instantaneous voltage and current belongs, cleared faults can be distinguished from uncleared ones.

3.3. Determination of the threshold

Linear discriminant analysis (LDA) is used to find the threshold which divides the UI-plane into two regions associated with cleared and uncleared faults [23].

Figure 7: Loci of voltage and current measurements as a function of time as well as the proposed characteristic for the local backup relay (solid line: uncleared fault, dashed line: cleared fault, dash-dotted line: backup relay characteristic)

LDA is a method that projects a set of samples into the direction which maximizes the separability among them. The projection of each sample (containing multiple features) into this direction results in a transformed sample with a lower feature dimension (in the new coordinate).

For the local backup relay, each sample x consists of two features (i^k, u^k) , which are the current and voltage measurements at the primary relay of the line for which the local backup is designed (cf. Fig. 5). These samples are obtained by applying a number of faults along their associated line while the primary breaker is either enabled or disabled. Within the time interval $[t_o, t_{d'}]$, the voltage and current measurements at the primary relay are sampled at instants $t_k = t_o + k\Delta t$ where Δt is a fixed time step. The obtained samples are divided into two sets, X_1 and X_2 , which are defined as the sets of samples associated with uncleared and cleared fault scenarios:

$$X_1 = \{(i_{uc}^1, u_{uc}^1), (i_{uc}^2, u_{uc}^2), \dots, (i_{uc}^K, u_{uc}^K)\},$$

$$X_2 = \{(i_c^1, u_c^1), (i_c^2, u_c^2), \dots, (i_c^K, u_c^K)\},$$

where K is defined such that $(t_0 + K\Delta t) \leq t_{d'}$.

For both sets, a matrix S_i is defined as

$$S_i = \sum_{x \in X_i} (x - \bar{x}_i)(x - \bar{x}_i)^T, \quad (1)$$

where $\bar{x}_i$ is the mean of X_i . The projection matrix w^* that maximizes the separability between samples of the two sets is:

$$w^* = S_W^{-1}(\bar{x}_1 - \bar{x}_2), \quad (2)$$

where S_W is the sum of S_1 and S_2 . Using w^* , the projection of samples x_i from X_1 and X_2 results in two new sets Y_1 and Y_2 with one-dimensional samples y_i , where

$$y_i = (w^*)^T x_i. \quad (3)$$

Cleared and uncleared faults are distinguished by comparing these projected samples to a threshold y_{thr} , which is defined as

$$y_{thr} = \frac{y_1^d + y_2^d}{2}, \quad (4)$$

where y_1^d and y_2^d are the closest samples from Y_1 and Y_2 , respectively.

4. Remote Breaker Failure Backup Relaying Algorithm

4.1. Overview

The remote breaker failure backup relaying algorithm deals with faults on remote buses in the forward direction of the relay. A fault in the forward direction can be in the relay primary protection zone, e.g., the line where the relay is located, or outside this zone, e.g., a remote bus or a remote line. For a remote bus

fault, the relay must provide remote backup protection in case the breaker associated with the bus primary protection fails. Remote backup protection for line faults is not considered in this paper since primary or local backup protection are required to clear those faults.

The remote breaker failure backup relaying algorithm uses voltage and current measurements to detect and identify uncleared bus faults in the forward direction of the relay. The remote backup protection is coordinated with the primary protection of the line at which these measurements are obtained. As an example, in the system shown in Fig. 5, faults on line AB, bus 1 and line CD are in the forward direction of the relay located at B, R^B . Faults on line AB are detected and cleared by the primary protection of line AB. The primary protection prevents the operation of the remote breaker failure protection. Faults at bus 1 which remain uncleared due to failure of the breaker located at A, are detected and cleared by the remote backup protection provided by the breaker located at B. Faults on line CD are either cleared by the primary protection (provided by the breaker located at C) or the local backup protection (provided by breakers located at A and E). For faults on line AB or line CD, no action from the remote backup protection is required.

4.2. Principle

The remote backup relaying algorithm must (i) detect faults, (ii) identify faults at remote buses and (iii) distinguish between bus faults cleared by the primary protection and uncleared ones. To achieve these objectives, the proposed backup relaying algorithm operates in three steps;

First, the relaying algorithm detects a fault in the forward direction if

$$\begin{aligned} u_r &< u_{\text{thr},d} \text{ and} \\ i_r &> 0, \end{aligned} \tag{5}$$

where u_r and i_r are the voltage and current measured at the relay and $u_{\text{thr},d}$ is a threshold. The time instant at which (5) is satisfied, is denoted with t_{det} . If after t_{det} , the primary protection system associated with the relay detects a fault in its primary protection zone, the primary breaker will trip instantly. If the primary protection system detects a fault outside its zone, the backup relaying algorithm will continue to operate.

Second, the relaying algorithm identifies faults at remote buses rather than remote lines. To identify a fault at a remote bus, at time instant t_{id} , u_r and i_r are compared against thresholds $u_{\text{thr},\text{id}}$ and $i_{\text{thr},\text{id}}$:

$$\begin{aligned} u_r &< u_{\text{thr},\text{id}}, \\ i_r &> i_{\text{thr},\text{id}}. \end{aligned} \tag{6}$$

If (6) is not satisfied, the relaying algorithm will detect a fault at a remote line and will not generate any trip signals.

The thresholds $u_{\text{thr},\text{id}}$ and $i_{\text{thr},\text{id}}$ allow the relaying algorithm to discriminate between faults at remote lines and remote buses. Traveling waves created by faults at a remote line encounter an additional series inductor in their path (from the fault location to the relay), compared to those created by a remote bus fault. Therefore, when the former waves reach the relay, their wavefront is less steep than that of the latter.

Third, the relaying algorithm detects an uncleared bus fault if, at time instant t_{uc} ,

$$u_r < u_{\text{thr},\text{uc}}, \tag{7}$$

where $u_{\text{thr,uc}}$ is a threshold. The remote backup relaying algorithm will generate a trip signal if (7) is fulfilled. If (7) is not satisfied, no trip signal will be generated. In (7), only a voltage-based criterion is used to discriminate between cleared and uncleared faults as this selection minimizes the required time. Due to the voltage inserted by the breaker surge arrester, the voltages measured at the relay for cleared and uncleared faults differ largely after t_o . By contrast, the measured currents for cleared and uncleared faults take similar values during the first 3 ms after t_o (Fig. 4).

A timer is used to control t_{id} and t_{uc} with respect to t_{det} . To distinguish cleared bus faults from uncleared ones, the delay between t_{det} and t_{uc} must be larger than the breaker opening time. To discriminate between remote line faults and bus faults, the delay between t_{id} and t_{det} must be less than t_{br} . Since the measured voltage for a cleared bus fault increases after t_o (Fig. 4), it becomes increasingly complex to distinguish cleared bus faults from remote line faults in case $t_{\text{id}} - t_{\text{det}} > t_{\text{br}}$.

Fig. 8 summarizes the steps and associated internal signals of the remote backup relaying algorithm as a function of time. The true value of flag signals s_d , s_i and s_u corresponds to fault detection outside the primary protection zone, remote bus fault detection and uncleared fault detection, respectively. If (5), (6) and (7) are fulfilled at t_{det} , t_{id} and t_{uc} , respectively, the internal signals will become 1. If all flag signals are 1 at t_{uc} , the remote backup relaying algorithm will generate a trip signal for its associated breaker.

Figure 8: Decisions made by the remote backup relaying algorithm as a function of time

5. Case Study

The local and remote backup relaying algorithms were applied to the test system of Fig. 1. The simulations were performed using PSCAD and a simulation time step of $5 \mu\text{s}$ was used. In this Section, the performance of the proposed backup relaying algorithms as B_{13} fails is discussed.

5.1. Local breaker failure backup protection

5.1.1. Threshold for breaker failure of B_{13}

To determine the threshold used by $R_{bf,l}^{13}$, 9 pole-to-pole faults were applied at equally-spaced distances on line L_{13} of the test system of Fig. 1. Detecting B_{13} failure with either a voltage threshold or a current threshold requires a precise time instant for the comparison of measurements against the single thresholds. As an example, the cleared and uncleared faults can be distinguished using a single current threshold after $t_o = 0.6 \text{ ms}$ (Fig. 9). By contrast, cleared and uncleared faults cannot be distinguished with a single voltage threshold after t_o . The reason is that the mean value of the voltage of the closest samples of uncleared and

cleared faults changes from 332.5 kV to 232 kV during the 1.2 ms time interval after t_o (Fig 9).

With the threshold proposed in Section 3.2, the samples associated with cleared and uncleared faults can be discriminated irrespective of the time instant at which the backup protection is expected to operate (Fig. 10). The threshold for B_{13} breaker failure detection is determined using the procedure described in Section 3.3. The associated scalar threshold y_{thr} is -0.9 and the projection matrix w^* is $\begin{bmatrix} 0.6493 & -0.017 \end{bmatrix}^T$.

5.1.2. Fault in the middle of L_{13}

The backup protection with the proposed relaying algorithm was evaluated for two fault scenarios. The two scenarios include a fault in the middle of line L_{13} . In scenario (i), the primary protection clears the fault and in scenario (ii), breaker B_{13} fails to interrupt the fault. For scenario (ii), a trip signal must be generated for breakers B_{12} , B_{14} and B_{1c} (breaker at the converter terminal). In this study, t_{br} and t_{pb} were set to 2 and 3 ms, respectively. The primary protection algorithm for R_{13} is the one proposed in [7].

A delay of at least 2 ms between t_d and backup action initiation is required to correctly distinguish between cleared and uncleared faults. At $t_d = 0.65$ ms, R_{prim}^{13} detects and identifies the fault in its primary zone (for both scenarios). During the 2 ms time interval of $[t_d, t_o]$, the projected samples for both scenarios exceed y_{thr} and are not separable. After t_o , the projected samples associated with the two scenarios can be separated using the threshold y_{thr} .

With the proposed backup relaying algorithm, the time interval during which the system is exposed to low voltages and high currents is limited. At $t'_d = 3.65$ ms, the backup relay generates a trip signal for all breakers at bus 1. These breakers

Figure 9: Loci of voltage and current for faults 1 to 9 along L_{13} ($\times$: cleared fault, $+$: uncleared faults)

clear the fault 11 ms after its inception.

The proposed backup relaying algorithm increases the speed of backup protection compared to those originally designed for ac system protection. For scenario (ii), the proposed backup relaying algorithm detects an uncleared fault at $t_{d'} = 3.65$ ms. With backup relaying algorithms developed for ac system protection,

Figure 10: UI-Threshold for B_{13} which separates cleared and uncleared faults and the samples of Fig. 9

Figure 11: Transformed samples y obtained by transformation of the voltage and current measured at R_{13} for a fault in the middle of line 13

breaker failure can be detected only after the expected fault clearance instant by the primary protection. For scenario (i), the primary fault clearance instant is at $t_c = 5$ ms, i.e., the instant at which the current through B_{13} returns to zero (Fig. 3). Therefore, the proposed backup relaying algorithm is at least 1.35 ms faster than using a relaying algorithm originally developed for ac system protection.

Due to the high speed of the proposed backup relaying algorithm, the max-

Figure 12: Current and voltage at R_{13} for a fault in the middle of line 13 cleared by the breaker failure backup protection

imum current through B_{13} is reduced. Since the maximum fault currents in the system are limited, short-circuit ratings for grid equipment can be reduced.

5.2. Remote breaker failure backup protection

The remote breaker failure backup protection provided by $R_{bf,r}^{31}$ was evaluated using the following scenarios: (i) a pole-to-pole fault at bus 1 cleared by bus 1 primary protection, (ii) a pole-to-pole fault at bus 1 and failure of B_{13} and (iii) pole-to-pole fault at L_{14} cleared by local backup protection (B_{13} , B_{12} and B_{1c} trip 3 ms after fault detection by R_{prim}^{14}). In scenario (iii), the fault occurs at 0 km from bus 1. The remote backup protection should trip breaker B_{31} for scenario (ii) and not take actions for scenarios (i) and (iii).

To determine the thresholds for $R_{bf,r}^{31}$, 16 fault scenarios were simulated and the resulting waveforms at $R_{bf,r}^{31}$ were analyzed. Along L_{14} and L_{12} , 9 and 5 fault scenarios were simulated at equally-spaced distances starting at 0 km from bus 1. These faults were cleared by the local breaker failure backup protection provided

by B_{14} and B_{12} , respectively. Two fault scenarios with a fault at bus 1 (which were either cleared by the primary protection or remained uncleared due to B_{13} failure) were also simulated.

The thresholds for the remote backup relay were derived from the waveforms of these scenarios and are shown in Table 1. $u_{thr,d}$ was chosen as 85% of the nominal voltage. The time delays were chosen such that t_{id} and t_{uc} are 1.5 ms and 3 ms after t_{det} , respectively. $u_{thr,id}$ was set to the minimum voltage measured at R_{31} after line fault detection. $i_{thr,id}$ was considered to be the maximum current measured at R_{31} at t_{id} . For $u_{thr,uc}$, the maximum value of the voltage measured at R_{31} for cleared bus faults was taken.

With the thresholds and time delays shown in Table 1, the remote backup relay generates a trip signal only for scenario (ii). For all fault scenarios, the backup relay quickly detects the fault, i.e., within 0.2 ms and 0.3 ms after wave arrival at $R_{bf,r}^{31}$ for scenarios (i)-(ii) and (iii), respectively (Figs. 13-14). At $t_{id} = 2.6$ ms, the relaying algorithm correctly distinguishes the fault at line L_{14} from the fault at bus 1. As s_{id} becomes 0 for scenario (iii), the backup protection does not take any action to clear the fault (Fig. 14 (c)). For scenarios (i) and (ii), at $t_{uc} = 4.3$ ms, the backup relay detects a cleared fault and an uncleared bus fault, respectively (Fig. 13). Only in scenario (ii), all flag signals become 1 (Fig. 13 (c)).

For scenario (ii), the maximum current through B_{31} is 7.13 kA which lies within the interruption capability of currently proposed dc breaker prototypes [8]. This current is reached at $t_{uc} = 4.3$ ms, when B_{31} trips. The fault current becomes zero at $t'_c = 5.8$ ms (Fig. 13 (a)). The current through B_{31} again increases after $t'_c = 5.8$ ms. This is due to the simplified model of the dc breaker, as no residual current interrupters are included. The used dc breaker model uses the voltage

inserted by the surge arrester to clear the fault.

Table 1: Remote backup protection settings

$u_{thr,d}$	$u_{thr,id}$	$i_{thr,id}$	$u_{thr,uc}$	t_{id}	t_{uc}
272 kV	113 kV	1.64 kA	181 kV	1.5 ms	3 ms

Figure 13: Scenarios (i)-(ii): (a)-(b): voltage and current measurements at R_{31} and (c) backup protection signals

6. Conclusion

This paper proposes two backup relaying algorithms to deal with local and remote breaker failure in HVDC grids. The proposed algorithms achieve a high operation speed by detecting primary breaker failure during its attempt to clear the fault. Due to the increased operation speed of the backup protection, the HVDC grid is exposed to low voltages and high currents for a shorter period of time. Furthermore, the maximum fault currents in the system are lower due to the

Figure 14: Scenario (iii): (a)-(b): voltage and current measurements at R_{31} and (c) backup protection signals

faster fault clearance. Therefore, required ratings of HVDC grid equipment can be largely reduced. Study results show that the algorithms reliably detect primary protection failure within only a few milliseconds.

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Acknowledgements

The research leading to these results has received funding People Programme (Marie Curie Actions) of the European Union’s Seventh Framework Programme FP7/2007-2013/ under REA grant agreement no. 317221, project title MEDOW.

The work of W. Leterme is supported by a Ph.D. fellowship from the Research Foundation-Flanders (FWO).