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A MISO FAULT DETECTION FOR HVDC GRIDS

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Abstract

Research on fault detection for high-voltage direct current (HVDC) grids has had a focus on single-ended DC fault detection using information from only the local line end. This paper proposes the use of additional information from neighbouring lines around the same busbar in a multiple-input single-output (MISO) fault detection. Simulations results show that the protection's dependability and security margins are increased which is particularly useful for remote faults in long lines with small line inductors. A discussion on practical implementation taking into account possible intellectual property (IP) aspects is added. A MISO fault detection can be useful to overcome some of the uncertainties due to missing knowledge about implementation details.

1 Introduction

Protection for high-voltage direct-current (HVDC) grids is a widely investigated topic. Several protection strategies and fault detection algorithms have been proposed as summarized in [1],[2]. Several industrial or partly industrial real-time simulation studies were presented [3]–[7] — all using intelligent electronic devices (IEDs) as hardware-in-the-loop. One complementary study using field measurements is available [8]. Furthermore, multiterminal HVDC grids (including protection systems) are in operation in China [9],[10].

Fault detection algorithms for HVDC grids are typically distinguished into single-ended algorithms using measurements from only the local line end; and double-ended algorithms using measurements from both line ends, thus requiring a communication channel. Using a communication channel is sometimes criticized as introducing unacceptable delays. However, it has been argued that double-ended fault detection is particularly useful (i.e., has a minimum communication delay) when single-ended fault detection reaches its limits in protection zone reach at the remote line end [2]. The argument on communication delays may not be as strong as it sometimes is perceived. Using information from the remote line-end is a reasonable complement to single-ended fault detection, particularly in long lines [2].

However, using information from the neighbouring local line ends at the same busbar has not been investigated. In the published literature, no fault detection algorithm makes use of information around the same busbar for primary DC line protection. Instead, individual functional units are typically used for each line end, regardless of whether they are implemented in one station IED or several DC line IEDs. A typical functional setup is shown in Fig. 1. Furthermore, the IED prototypes in [3]–[5] use individual functional units for each line end and only communicate among these local functional units in case of a protection backup situation.

Fig. 1: Typical functional setup of DC line fault detection

This paper investigates the use of additional information at the same busbar for the primary protection and presents a multiple-input single-output (MISO) structure for fault detection in HVDC grids. The remainder of this paper is structured as follows. The MISO approach is explained in more detail in Section 2. The simulation setup is described in Section 3. The results of the performed studies are presented in Section 4. Section 5 provides the discussion of results and Section 6 the conclusion.

2 MISO Fault Detection

For a MISO fault detection for DC lines in HVDC grids, it is proposed to complement the local fault detection, e.g., using a dv/dt criterion, with additional information from the neighbouring lines around the same busbar. For that, the fault detection signal shall be increased or decreased by 10 % of the threshold value – depending on the fault detection signal on the neighbouring links (j, k) compared to the local link i. Note, that the protection margins are assumed with $\pm 50\%$ around the protection threshold. The proposed functional setup of a DC line fault detection using a MISO approach is shown in

Fig. 2: Functional setup of a DC line fault detection using a MISO approach

Fig. 3: DC line protection with MISO approach; shown example with dv/dt criterion

Fig. 2. A flowchart detailing the proposed MISO HVDC fault detection is shown in Fig. 3.

If the local link i produces a fault detection signal that reaches at least 50 % of the threshold, this is a strong indication for a fault on that link. To further increase dependability, the fault detection of the neighbouring links is investigated. If both neighbouring links (j, k) stay below 50 % of their thresholds, the fault detection signal of the local link i is increased by 10 % of its threshold value.

If any of the neighbouring links reaches 90 % of their respective thresholds, this is taken as an indication that a fault likely appeared on that link and not the local link i . To further increase security, therefore the local fault detection signal is decreased by 10 % of its threshold value.

3 Simulation Setup

The reference HVDC grid for this study is shown in Fig. 4. The use of half-bridge modular multilevel converters (MMCs) and DC circuit breakers (DCCBs) is assumed because both technologies are considered established. MMCs are widely used

in HVDC systems. DCCBs are in operation in several Chinese HVDC grids or have been tested full-scale [11]. The HVDC test grid has a DC voltage of ± 320 kV and uses a symmetrical monopole arrangement. The PSCAD implementation is based on the system available in [12]. All faults have 10 m Ω fault resistance. A fault detection characteristic (including delays), similar to the prototype in [13] is implemented. The fault detection uses a dv/dt algorithm at 50 kHz sampling. For the underlying communication required for the MISO element, 30 μ s of communication delay are implemented. The main interest in this study is in busbar 1 where the MISO fault detection will be compared with a pure dv/dt fault detection. All thresholds are set to 15 kV/sample ($= 0.75$ kV/ μ s). An identical threshold value is chosen for all lines to reduce the number of variables impacting the protection margins when investigating a MISO approach. A proper protection design would likely result in different threshold values for cables of different lengths such that the complete cable is covered with a single-ended fault detection.

Fig. 4: HVDC test system based on [12]

4 Results

Many hardware and software aspects are relevant for the secure and dependable design of HVDC protection. Here, only two main factors impacting protection margins will be investigated. Only results for pole-to-pole faults are shown here. The behaviour for pole-to-ground faults is comparable.

4.1 Short Cable — Long Cable

The impact of adding a MISO element to a purely local fault detection (“MISO- dv/dt ”) is shown for different line lengths in Fig. 5 (shortest line 12, 100 km) and Fig. 6 (longest line 14, 400 km). Both examples use 50 mH line inductors.

First, only the local dv/dt fault detection (without MISO element) will be discussed. It can be observed that the shorter line 12 has higher dependability margins (above threshold) than the longer line 14. This is due to the higher line impedance in the longer cable that dampens the voltage collapse following a fault, thus decreasing the dv/dt to be detected in the fault detection. Secondly, the fault detection signals of all non-faulted lines are well below the threshold around 0.2 p.u.

Adding a MISO- dv/dt element increases the dependability margins (above threshold) by 10 % of the threshold value. Furthermore, adding a MISO- dv/dt element increases the security margins by decreasing the fault detection signals of non-faulted lines with 10 % of the threshold value. Note, that in the figures, the fault detection signals on the non-faulted lines is not in all cases decreased by 10 % (even though this is implemented in the algorithm). The figure captures the maximum fault detection signal recorded during the transient following the fault. However, the MISO-input reducing the fault detection signal by 10 % arrives with 30 μ s delay and may not coincide with the maximum dv/dt signal.

In general, there is little impact of adding a MISO- dv/dt element to a purely local fault detection for different line length when using a 50 mH line inductor.

4.2 Large Line Inductor — Small Line Inductor

The impact of adding a MISO element to a purely local fault detection (“MISO- dv/dt ”) is shown for different line inductors in Fig. 5 (50 mH) and Fig. 7 (25 mH) for the shortest line 12, and in Fig. 6 (50 mH) and Fig. 8 (25 mH) for the longest line 14.

First, only the local dv/dt fault detection (without MISO element) will be discussed. The line inductor size has a negligible impact on the fault detection signal on a faulted line going above threshold (line 12 in Fig. 5 and Fig. 7 or line 14 in Fig. 6 and Fig. 8). However, the line inductor size has an impact on the fault detection signal on the non-faulted lines with a fault detection signal below threshold. By reducing the line inductor size from 50 mH to 25 mH the fault travelling wave is damped

Fig. 5: Comparison of algorithm output for dv/dt (left) and MISO- dv/dt (right), 50 mH line inductors, pole-to-pole faults on line 12 (100 km)

Fig. 6: Comparison of algorithm output for dv/dt (left) and MISO- dv/dt (right), 50 mH line inductors, pole-to-pole faults on line 14 (400 km)

Fig. 7: Comparison of algorithm output for dv/dt (left) and MISO- dv/dt (right), 25 mH line inductors, pole-to-pole faults on line 12 (100 km)

Fig. 8: Comparison of algorithm output for dv/dt (left) and MISO- dv/dt (right), 25 mH line inductors, pole-to-pole faults on line 14 (400 km)

Fig. 9: Zoom into Fig. 8, algorithm output for dv/dt (left) and MISO- dv/dt (right), 25 mH line inductors, pole-to-pole faults on line 14 (400 km)

less when moving through the DC bus such that the voltage collapse (and dv/dt fault detection signal) is stronger in the 25 mH case compared to the 50 mH case. Therefore the fault detection signals of all non-faulted lines are increased to around 0.2 p.u. to 0.4 p.u. in the 50 mH cases which is closer to the protection threshold.

Again, adding a MISO- dv/dt element in the 25 mH cases increases the dependability margins (above threshold) by 10 % of the threshold value. Similarly, the fault detection signals of the non-faulted lines are decreased with a MISO- dv/dt element to ca. 0.1 p.u. less than without MISO- dv/dt element. This is useful in particular for the long line 14 with small line inductors of 25 mH.

A zoom into the fault detection signals for line 14 and 25 mH line inductors is shown in Fig. 9. It can be observed that the addition of the MISO-element reduces the fault detection signals of the non-faulted lines (more security margin) and increases the fault detection signals of the faulted lines (more dependability margin). The latter is particularly useful for remote faults (case e) with a distance of 400 km, where the fault travelling waves are dampened through the cable impedance.

5 Discussion

This study uses an identical threshold for all line lengths and inductor sizes. While this would not be the case in reality, it still allowed to investigate the impact of a MISO fault detection

under different line lengths and line inductor sizing — without changing more parameters.

Remote faults in long cables are typically harder to detect using only local information from one line end. The threshold setting to achieve selective protection depends on the chosen line inductors. In general a larger line inductor is preferred in terms of selectivity, but not favourable in terms of controllability. If a long line shall be equipped with small line inductors, using a MISO-element can complement the local fault detection such that the security and dependability margins are increased. However, it cannot be concluded from the presented study how this change in the local fault detection relates to a potential other complement using double-ended fault detection including communication between the line ends.

It can, however, be argued that increasing the security and dependability margins is useful in HVDC systems. An earlier study [14] showed that missing knowledge on, e.g., the IED sampling and software filtering, the algorithm used, and also the surge arrester characteristics can – in unfavourable combination – consume a considerable portion of the protection margins, even leading to unwanted trips. While a statement on the design of a protection system obviously depends on the specific case study, in general, it can be argued that increasing protection margins using knowledge from the same local busbar, can help overcome the problem of decreased margins due to missing knowledge — while not having to touch upon vendor IP, such as the implemented IED software filter.

Fig. 10: Possible concepts for a practical implementation
(a) Several MISO units
(b) One MIMO unit

As regards a practical implementation, two main options can be conceived. The first option is shown in Fig. 10a where several line DC line protection IEDs receive information from neighbouring lines, thus allowing for a MISO DC line protection. The advantage of this implementation is that the vendor IP is respected by keeping the fault detection algorithms black-boxed within a hardware device. The information to be communicated can be of binary nature without having to disclose information about the fault detection algorithm (compare Fig. 3). The disadvantage of this setup may be the need for a more complex communication compared to the concept in Fig. 10b using only one DC line protection IED covering all lines. That latter concept only requires the measurement inputs from the lines connected to the busbar thus simplifying communication. A disadvantage of the concept in Fig. 10b may be seen in the fact that one MIMO DC line IED would possibly operate DCCBs of other vendors – which would require careful coordination to respect the DCCB limits.

6 Conclusion

In this paper, a new proposal for a MISO HVDC fault detection using information from neighbouring lines on the same DC busbar was proposed. The proposed MISO fault detection was investigated in simulation studies for different line lengths and different line inductor sizes where both the dependability and security margins could be increased. An implementation using several line IEDs with real-time communication using binary information may be beneficial to not touch upon vendor IP. In general, it can be concluded that a MISO HVDC fault detection is most beneficial for long lines with small line inductors.

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