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# Advanced fault location in MTDC networks utilising optically-multiplexed current measurements and machine learning approach

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ABSTRACT

This paper presents a method for accurate fault localisation of DC-side faults in Voltage Source Converter (VSC) based Multi-Terminal Direct Current (MTDC) networks utilising optically-multiplexed DC current measurements sampled at 5 kHz, off-line continuous wavelet transform and machine learning approach. The technical feasibility of optically-based DC current measurements is evaluated through laboratory experiments using commercially available equipment. Simulation-based analysis through Matlab/Simulink® has been adopted to test the proposed fault location algorithm under different fault types and locations along a DC grid. Results revealed that the proposed fault location scheme can accurately calculate the location of a fault and successfully identify its type. The scheme has been also found to be effective for highly resistive fault with resistances of up to 500 Ω. Further sensitivity analysis revealed that the proposed scheme is relatively robust to additive noise and synchronisation errors.

## 1. Introduction

High Voltage Direct Current (HVDC) power transmission are becoming increasingly competitive compared to high-voltage-alternating-current (HVAC) power transmission, especially for bulk power transmission over long distances. This is because of many commercial and technical advantages introduced by HVDC transmission systems, utilising the most recently developed voltage source converters. Those advantages include bulk power transfer (notably from offshore wind [1]) over long distances [2], upgrading existing AC networks [3], interconnection of asynchronous grids and black start capability [4].

HVDC networks based on Modular Multilevel Converters (MMCs) is becoming progressively more favourable by the virtue of superior advantages, such as high efficiency, flexible control, scalability, and remarkable power quality with low harmonic content [5]. Further technical and economical improvements can arise by introducing MTDC systems which consist of more than two VSC stations and consequently the formation of a DC grid [6].

The majority of the existing operational and planned HVDC links are point-to-point with two points of connection with the AC networks. These connections are utilised for long distance power transmission within a country or for interconnection among different countries. At present, there is only one MTDC grid in operation located in Zhoushan, China, which was commissioned in 2013 [7]. However, with an increased penetration of renewable energy sources, balancing the supply and demand is likely to be one of the major challenges in future power systems [8]. Consequently, there is a growing need for meshed interconnections between countries in order to effectively share the available power capacity and thereby increase operational flexibility and security of supply. This has been raised as a major issue in Europe but also in Asia and United States of America. Before MTDC grids are widely adopted, it is essential to analyse the imposed potential challenges, like transient fault response [9], system integration, stability and power flow control [10].

After the occurrence of a feeder fault on a transmission system, protection systems are expected to minimise its detrimental effects, by initiating clearing actions such as selective tripping of circuit breakers. Following the successful fault clearance, the adjacent action is the accurate estimation of its location with regards to feeder's length. This is of major importance as it will enable faster system restoration, diminish the power outage time, and therefore enhance the overall reliability of the system. Therefore, this paper deals with the challenges involved in fault location of DC-side faults in MTDC systems.

The proposed scheme is based on a network of distributed current sensors installed at each feeder of an MTDC grid, and the subsequent travelling wave detection from DC current signatures. The accuracy of the proposed scheme is enhanced by the adoption of a machine learning approach, based on a pattern recognition scheme. The idea of

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distributed current sensors has been previously developed by the authors in [11] for protection applications in MTDC networks. The structure has been significantly expanded to be suitable for fault location applications in MTDC networks.

The remainder of the paper is organised as follows: Section 2 presents a literature review on the existing and proposed fault location techniques. Section 3 proposes and explains in detail the proposed fault location scheme. Section 4 presents the results of a thorough simulation-based evaluation of the proposed scheme. Section 5 introduces the optical sensing technology and presents a series of experimental results, demonstrating the technical feasibility of optically-based DC current measurements. Finally, in Section 6 conclusions are drawn.

## 2. Fault location in HVDC systems

Travelling Waves (TWs) have been proposed as a very accurate solution for fault location both in AC and DC networks. According to the number of measurement points, TW-based fault location can be divided into single-ended and two-ended. The first one requires two consecutive waves to calculate the fault location. The two-ended methods requires the first waves, captured and time-stamped from both ends of a feeder.

The basic principle of single-end TWs alongside with two graph theory-based lemmas are utilised in [12] to locate the faults in MTDC networks. Nevertheless, high sampling frequency (1 MHz) is required, while detecting the first wavefront could be challenging [13]. A two-ended method based on Wavelet Transformation (WT) is utilised in [14] to locate faults in hybrid HVDC systems with both overhead lines (OHLs) and cables. The method requires voltages and capacitor current measurements, sampled at 2 MHz.

Another application of WT is utilised in [15] to accurately locate the faults in star-connected MTDC systems. The method necessitates measuring DC terminal currents and can eliminate the need of repeater station placement at the network junctions. However, both methods presented in [14,15] suffer from the need of time-synchronised measurements and high sampling frequency (2 MHz). Additionally, highly resistive faults have not been investigated thoroughly. In [16] a TW-based method is proposed by utilising voltage and current measurements from both ends of the faulted feeder. The method eliminates the need of both synchronised measurements and estimation of line parameters, and has been found to be accurate for both metallic and highly resistive faults (up to 500 Ω). However, there is a need for high sampling frequency (1 MHz). The method proposed in [17] eliminates the need to identify the precise arrival time of the surges. The proposed idea utilises the natural frequency of TWs (i.e. the dominant natural frequency in the spectrum analysis of TWs). For the execution of the algorithm, voltage and current measurements from one end (sampled at 100 kHz) are required. Even though the method has been found to be accurate, it has been tested only for highly resistive faults up tp 50 Ω.

Different from those methods which utilise TWs a few others can be found in the literature. In [18] the voltage distribution across the Bergeron line model is calculated in order to calculate the location of the fault. The sampling frequency required is only 6.4 kHz, while the method is accurate for long transmission lines and with highly resistive faults up to 500 Ω. However the method still requires time-synchronised measurements. The article in [19] reviews the methods for diagnosing and locating faults in submarine power cables using the principles of reflectometry [20], with case studies relevant to very long HVDC cables. Emphasis is put on the differences in the conditions and methods between locating a fault on a submarine cable from land cables, and the best practices for diagnosing and locating these types of faults are discussed. Even though that actual methodologies and test results are not presented thoroughly, it can be deduced that the need for external equipment and high sampling rates are drawbacks of these methods.

A special category of fault location practices (which is highly-related to the focus of this paper) incorporates the utilisation of learning-based approaches. Even though that such intelligent methods have been extensively used for localisation and classification of faults in AC networks [21–25], there is a limited number of publications which indicate their appropriateness for analysis of DC-side faults [13,26,27]. For example, based on post-fault voltage measurements sampled at 80 kHz, a method based on voltage similarity is proposed in [13]. The distance is calculated by calculating the Pearson coefficients with pre-simulated test patterns. Based on TWs and Support Vector Machine (SVM) another method is proposed in [26]. The method is single-ended and requires both current and voltage measurements. However the study cases consider fault resistance values up to 70 Ω, while the sampling frequency needs are not clearly stated.

**Table 1**
Review of challenges related to fault location categories.

| Fault location category | Challenges |
|---|---|
| Travelling waves | • Requirement of high sampling frequency<br>• Difficulties in detection of initial wave<br>• Speed of propagation should be known<br>• Impact of highly-resistive faults<br>• Need for time-synchronised measurements (two-ended method) |
| Reflectometry | • Need for external equipment<br>• High sampling frequency in the range of MHz to GHz<br>• Site visit to the feeder's terminal and assembly/disassembly of testing equipment |
| Learning-based | • Training of the system is required. Since fault records are not always sufficient (or sometimes not available at all) the training is usually implemented by simulation-based iterative studies. This could raise concerns with regards to the reliability of the system training |

Most of the fault location methods for HVDC lines can be classified in three major categories namely, 'TW-based', 'reflectometry-based' and 'learning-based'. A literature review of the methods falling under the three aforementioned categories revealed that there is a wide selection of options which can accurately calculate the location of a fault. However, they are all accompanied by some technical challenges and barriers which are summarised in Table 1.

## 3. Proposed fault location method

The fault location algorithm proposed in this paper is based on the availability and feasibility of optically-multiplexed current measurements (further analysis will be provided in Section 5). Such an experimental arrangement has been used previously in [11] for high-speed protection applications in MTDC networks. Therefore, the scheme has been significantly expanded to be suitable for fault location applications in MTDC networks.

The fault location technique consists of three main stages and utilises data buffers to store and process DC current records from all the available sensors along the faulted line. The flow chart of the fault location algorithm is depicted in Fig. 6 and the stages are analysed in detail in the following subsections. It should be noted that prior to any signal analysis for the calculation of fault location, the optical signals are modulated and converted in DC current/voltage. This will be further analysed in Section 5.

### 3.1. Stage I: Fault classification

Fault type is classified based on the post-fault DC current signatures. The possible types of fault include Pole-to-Pole Fault (PPF), Positive pole-to-Ground Fault (PGF) and Negative pole-to-Ground Fault (NGF). These have been assumed based on the relevant technical literature, addressing challenges arising from DC-side faults in VSC-based HVDC