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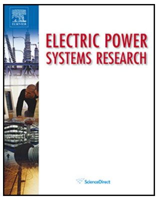

A single-ended fault location method for segmented HVDC transmission line

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ABSTRACT

This paper presents a single-ended traveling wave-based fault location method for segmented high voltage DC (HVDC) transmission lines; an overhead line combined with an underground cable. DC transient voltage and current signals at the sending-end of the overhead line are assumed to be available. Discrete Wavelet Transformation (DWT) is then applied to the DC voltage and current signals. The wavelet energies of voltage and current transients over 16 ms (i.e. 1-cyle in 60-Hz frequency) are calculated and then normalized. The normalized energies are used as the input to a binary Support Vector Machine (SVM) classifier for faulty section identification (underground cable or overhead line). Once the faulty section is identified, the faulty-half is determined by comparing polarity of the first two current traveling waves. Bewley diagrams are finally observed for the traveling wave pattern and the wavelet coefficients squared of DC voltage are used to locate the fault. The transient voltage and current for different fault locations are simulated using the ATP software. MATLAB is used to process the simulated transients and apply the proposed method. The performance of the proposed method is evaluated for different fault locations and fault resistances. The impacts of non-linear high impedance faults (NLHIF) and cable aging are also studied.

1. Introduction

1.1. Motivation and literature review

HVDC transmission systems have increasingly been used in modern power transmission networks due to many advantages, such as, providing higher power transmission capability over long distances, interconnecting asynchronous systems and having the potential for accommodating very-large scale intermittent electrical energy (i.e. wind and solar). The European supergrid is an HVDC transmission system proposed to transmit renewable energy-based electrical power from the remote locations to the load centers [1]. Combination of overhead lines and underground cables has been deployed as a segmented HVDC transmission system when two networks separated by water need to be connected [2]. In addition, underground cables are utilized to connect offshore wind farms to the existing grid through overhead lines [2]. However, the complexity of fault location problem increases with the proliferation of such unusual topologies.

Accurate and fast detection and location of faults along HVDC transmission lines are vital to improve power system reliability and availability. Traveling-wave based fault location method is proposed for HVDC transmission lines in [2–8]. The traveling wave-based methods have high accuracy and the results are not affected by the parameters, such as ground resistance or loading conditions. Traveling-wave based methods are grouped into two subcategories with respect to the measurements they employ at the receiving and/or sending ends of the transmission lines:

- single-ended, and
- multi-ended (synchronized).

In [3,4], a single-ended fault location method for HVDC transmission systems with overhead line is proposed. Current traveling waves are used for fault location. Dewe et al. [5] proposes a two-ended traveling wave-based fault location method for a two-terminal HVDC transmission system. Arrival times of the fault initiated traveling waves at both ends of the line are detected using global positioning system (GPS). In [6], a traveling wave-based faulty-pole selection and protection scheme are proposed and implemented. De Kerf et al. [7] presents a single-ended fault location and protection scheme for multi-terminal HVDC systems. The proposed fault location and protection is based on continuous wavelet transformation (CWT) of measured DC voltage. Tang

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and Ooi [8] proposes a fault location and isolation method in multi-terminal HVDC systems. The main purpose of the proposed method is to develop a protection scheme which uses AC circuit breaker to clear the fault.

The use of discrete wavelet transform (DWT) in high voltage AC (HVAC) overhead transmission line fault location problem is first proposed in [9]. DWT is applied to the aerial mode voltage to extract the traveling wave information from the recorded transients. In [10], a two-ended fault location method using wavelet transformation is proposed for HVAC overhead transmission systems. Borghetti et al. [11] proposes the use of CWT for fault location in distribution networks where the section of the fault is first estimated based on the observed characteristic frequency, which is obtained by using wavelet energies scalogram. In [12] the initial estimate is then improved by using the time differences between the local maxima of continuous wavelet transformation coefficients corresponding to the identified characteristic frequency. Zhao et al. [13] and Jung et al. [14] present traveling wave-based fault location methods for HVAC underground cables using DWT. Zhao et al. [13] proposes a two-ended traveling wave-based fault location for underground cables with synchronized measurements at both ends. Jung et al. [14] presents a single-ended traveling wave-based fault location for underground cables and uses DWT to cancel the noise and detect the arrival instant of waves observing the correlation between wavelet scales.

A single-ended fault detection and location method for HVDC transmission systems using DWT is first proposed in [15]. The two-ended traveling wave-based fault location method for a HVDC transmission system is implemented in [16]. A two-ended fault location method for overhead HVDC transmission line using steady-state voltages and currents is proposed in [17]. The proposed method is based on the distributed parameter line model. The DC voltages at discrete points along the DC line are calculated using the voltage and current measurements from both terminals, separately. The fault location is then estimated by comparing the calculated voltages from both ends.

The main challenge in traveling wave-based fault location for combined overhead line and underground cable is faulty section identification. This challenge is due to the reflections of the fault signal from the joint-point and the fault point as well as the unequal traveling wave velocities in line and cable. Fault location methods for segmented HVAC transmission lines consisting of an overhead line and an underground cable are proposed in [18–22]. Eldin et al. [18] and Liu et al. [19] propose phasor-based methods which utilize the synchronized voltage and current measurements from both ends of the transmission line. In [20] an adaptive neural network-fuzzy approach is used to locate the fault accurately in a combined transmission line using fundamental components of post-fault measured voltages. Jung et al. [21] presents a wavelet and neuro-fuzzy based fault location method. Voltage and current DWT detail coefficients (i.e. traveling waves) are used as the input for faulty section identification. The impedance-based fault location method is then utilized which is dependent on fault type. In [22], a single-ended traveling wave-based fault location method for combined transmission lines is proposed. The voltage traveling wave's polarity change is used to identify the faulty section. The time delay between traveling waves is then used to calculate fault location. For segmented HVDC transmission lines, a two-ended traveling wave-based fault location method is proposed in [2,23]. CWT is utilized to detect the arrival times of traveling waves at both terminals. The fault location is then calculated using the detected arrival times of traveling waves at both ends. This paper proposes a new traveling wave-based fault location method for segmented HVDC transmission lines. Support vector machine (SVM) and discrete wavelet transformation (DWT) are utilized for faulty section identification and fault location. Following is an overview of the use of SVM for fault location in HVAC transmission lines.

Support vector machine (SVM) is a statistical data classification method, which finds the maximum marginal boundary between different classes of a given data set and provides the global optimal solution. This property is recognized as the main advantage over Artificial Neural Network (ANN) based classification methods. The use of SVM for faulty section identification in HVAC transmission systems is proposed in [24–29]. In [24] steady-state post-fault voltages and currents are used as the input to the SVM classifier, while the current transients are the inputs to the SVM faulty section identifier in [25] and voltage transients are utilized as the input to the SVM in [26]. The proposed method in [25,26] are dependent on the fault type. In [27] fault location in transmission lines using SVM-Neural Network with voltage and current transients is proposed. The proposed method assumes that the fault type is known and the SVM corresponding to the fault type is used. Jiang et al. [28,29] propose a fault classification and location method for power system based on wavelet transform, SVM and ANN. The wavelet transformation coefficients of three-phase voltage and current transients are used as the input to the SVM fault classifiers. The ANN is then used for fault location according to the identified fault type.

1.2. Contribution and paper organization

This paper presents a single-ended fault location method based on traveling waves for a segmented HVDC transmission line, which is composed of an overhead line combined with an underground cable. This paper utilizes and extends the results of the method presented in [30,31,32] to a segmented HVDC transmission line. The proposed method uses SVM to identify the faulty section. The main contributions of the paper are as follows:

- The fault location method is carried out using single-ended measurements.
- The proposed method uses SVM for faulty section identification.
- The proposed SVM classifier uses a two-dimensional input for decision making.

This paper is organized as follows: In Section 2, the fundamentals of SVM classifiers are briefly reviewed. In Section 3, the proposed fault location method based on DWT and SVM is presented. Simulation results are provided in Section 4 followed by the conclusions in Section 5.

2. Review of support vector machines

Support vector machine (SVM) was first introduced by Vapnik as a binary linear classifier. The SVM classification finds an optimal hyperplane to separate data sets with two different classes ({+1, −1}). The linear hyperplane is defined by a weight vector W and a bias term b as:

$$W^T x + b = \begin{cases} \geq 1, & class + 1 \\ \leq -1, & class - 1 \end{cases} \tag{1}$$

Fig. 1 shows the separating hyperplane in a 2-dimensional space. The separation margin (m) between two classes is given as [33]:

$$m = \frac{2}{||W||} \tag{2}$$