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A novel and comprehensive single terminal ANN based decision support for relaying of VSC based HVDC links

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ABSTRACT

HVDC technology is increasingly important for long distance bulk power transmission, but existing protection relaying techniques for such a system are subject to limitations. This paper presents a novel Artificial Neural Network (ANN) based on an algorithm for fault detection, location and classification in VSC-HVDC systems. Taking advantage of the ability of ANNs to identify and classify patterns, the proposed algorithm is able to detect and correctly classify a fault occurring at either the rectifier substation on the DC line or at the inverter substation. Therefore, such a scheme can be used as a decision support tool or as a backup protection. Only local signals are used at the rectifier substation and no communication link is necessary, thus improving the system's protection reliability and reducing the overall cost of the hardware implementation. A detailed VSC-HVDC system is described and used to simulate a number of fault scenarios in the system. Using the resulting fault waveforms, a comprehensive decision support scheme is developed and described, paying particular attention to the signal processing chain and design of the specific ANNs for each relaying task. Finally, a detailed analysis of the influence of key fault parameters on the limits of the algorithm's performance is carried out.

1. Introduction

Currently, High Voltage Direct Current (HVDC) transmission systems are the best option to transfer a large amount of power over long distances. The advantages are: the ability to interconnect asynchronous systems; fewer losses compared to High Voltage Alternating Current (HVAC) systems; improvements in power system stability; smaller power towers; and a narrower transmission corridor meaning less rights of way. In spite of the technical, economical and environmental advantages, HVDC systems pose many challenges for power protection engineers as the transient behavior of very long DC lines and complex terminal converter stations should be modeled to study the system's post fault response.

In order to safely operate HVDC systems, it is important to detect and clear any fault which occurs in the HVDC system as soon as possible [1–3]. For this purpose, the most common HVDC protection systems are based on the travelling wave theory [4–10], the DC voltage level [11] and differential voltage measurement [12] techniques, the rate of voltage change technique [13] and the current differential scheme [1–3,13]. The rate of voltage change and DC voltage level techniques are normally used as a main protection to detect single phase faults. However, some problems can arise concerning high resistance or multi-phase faults [4–6]. Conventional current differential schemes are commonly used as a backup protection, but they are affected by the capacitance of long lines. In addition, they require a communication link and the information must be synchronized between the two ends [14]. Travelling wave based methods still experience problems concerning their practical application since they are very dependent on the high sampling rate, and are therefore difficult to implement, even in hardware. Moreover, this method can be easily influenced by noise [6,7,11].

In an attempt to overcome all the aforementioned challenges, researchers are working on novel methods to protect HVDC systems. The method presented in Ref. [4] is based on symmetrical components and travelling waves for fault classification and faulty pole selection. Ref. [5] describes a new transient harmonic current protection scheme to identify the type of fault. This method uses the DFT to extract information from both terminals of the DC transmission line. In Refs. [6,7], a hybrid method is shown combining travelling waves and a boundary protection scheme for bipolar HVDC lines. This method was implemented and evaluated in real time using programmable logic devices. Research carried out in Ref.

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[8] presents a new scheme for fault location based on the natural frequency of a distributed parameter line model. In this proposal, only currents from the sending terminal are used and the natural frequency is obtained by the PRONY algorithm. A method for fault location also based on the travelling wave theory is presented in Ref. [9], where Discrete Wavelet Transformation is applied to the voltage and current signals only at the relay terminal and the fault location can be estimated in a segmented HVDC transmission line. The scheme presented in Ref. [10] uses a method based on distance protection to enhance the fault distance estimation for faults nearest the remote terminal, and is able to distinguish internal faults from external faults.

As the protection relay of HVDC systems presents complex problem spaces, an alternative approach is to use Artificial Intelligence [15], more specifically Artificial Neural Networks (ANNs) [16–23]. Such techniques are appropriate when the conventional approaches do not appear as an effective solution. Most of them describe methods using a pre-processing stage coupled with a Multi Layer Perceptron (MLP) neural network [16–19], but significant variations on this theme exist, including using adaptive linear neurons [20], radial basis function neural networks [21] and ANNs optimized by the particle swarm theory [22]. Still considering MLP neural networks, a scheme to detect and classify faults in a HVDC line, presented in Ref. [23], should be highlighted. It is important to note that this scheme is only able to operate for DC faults, by using a very high sampling rate, which makes it more complex to implement. Furthermore, cases considering different fault resistances and non-nominal conditions were not considered. As will be discussed later, the solution proposed in the current paper overcomes these limitations.

The work herein presents a solution based on ANN, specifically a feed forward MLP to support the protection scheme of the whole HVDC system, i.e., the rectifier substation, the DC transmission line, and the inverter substation. It is important to highlight that the main focus and contribution of this paper is to clarify and discuss some different possibilities to improve the protection scheme of HVDC systems using ANNs. In addition, it is shown how the outputs of several ANNs, each designed for different purposes, can be combined together with logic gates to improve the robustness and extend the overall protection of the algorithm's operational range.

In order to develop ANNs and evaluate the proposed algorithm, a VSC-HVDC system is modeled and simulated in MATLAB Simulink's Power System Blockset (PSB). A large number of fault cases were generated by varying different fault locations, types of fault, fault resistances and power across the DC transmission line. This paper is organized as follows. In Section 2, the VSC-HVDC system used is presented and its settings and characteristics are discussed. In Section 3, the proposed algorithm is described in detail. In particular, the training process, pre and post processing and ANN validation criteria are included. In this section, the algorithm is evaluated regarding the training space and signals from PSB/Simulink. In Section 4, the limits of the proposed algorithm are evaluated and a study about accuracy and response time is presented. Finally, the conclusions are drawn in Section 5.

2. VSC-HVDC system model in PSB/Simulink

Fig. 1 shows the single line diagram of the VSC-HVDC system used in this work to generate a wide range of fault cases. The output waveforms were used to generate RMS values to be used in the ANN training process and to evaluate the final algorithm's performance. This system was modeled and validated in MATLAB [24] and it is essentially representative of a symmetric monopole configuration with Neutral Point Clamped (NPC) and 12-pulse converters on both the rectifier and inverter sides. The nominal voltage at the DC link is ±100 kV and the rated transmission power is 200 MVA. Regarding the AC sides, both operate with a nominal voltage of 230 kV (50 Hz) and the short-circuit power is 2000 MVA. More details about the used VSC-HVDC system are included in Appendix A, where Figs. A1 and A2 present the AC systems connected at buses 1 and 2, respectively. Similarly, Figs. A3 and A4 present the AC and DC filters connected at the rectifier and inverter side, respectively. Table A1 shows the VSC-HVDC parameters.

To model the distributed nature of the line's parameters more closely, the original "π" model 75 km length DC transmission line was replaced by a DC transmission line with 40 "π" sections, which is sufficient to accurately represent a DC transmission line of 200 km length [25], used in this work.

As can be seen in Fig. 1, the whole system consists of AC equivalent sources, AC and DC filters, capacitors, phase and smoothing reactors and a data acquisition system, only at the rectifier substation. At bus 1, the RMS AC voltages (Va, Vb, and Vc) and the values of the voltage and current (Vd and Id) of the faulted pole in the DC line are available. It is important to highlight that the proposed decision support scheme only uses these available RMS values and DC quantities, provided by existing meters. Vd and Id are averaged to give the mean values of the voltage and current (Vd and Id) over the last 20 ms, equivalent to one cycle at 50 Hz. It is assumed that the data acquisition system is supplied with AC and DC transducers with sufficient bandwidths. Once the algorithm developed here uses RMS AC values and time averaged DC values, this is a realistic assumption since the transducers only need to provide an accurate response up to the AC system frequency.

In terms of fault types and fault locations on the AC side, all common fault configurations are simulated. On the DC side, only pole-to-ground faults are simulated, because pole-to-pole faults can only be caused by sufficient physical damage to bring the conductor poles together and, therefore, they are very rare [2]. In addition, Ref. [26] states that pole-to-pole faults on the DC cables are considered unlikely if the two poles are laid in separate cables with some distance in-between.

3. Proposed algorithm based on ANN

The main concept behind this proposal is to use the ANN classification and pattern identification capability to support the protection scheme of the HVDC system presented in Section 2. Signals are collected at the rectifier substation and processed by the algorithm providing a mechanism to generate a trip signal or any other pre-defined control actions. Fig. 2 shows all the input signals used by the algorithm, as well as the processing steps involved. The main part of the algorithm is an ANN using RMS three phase values and DC quantities to detect the operational condition of the HVDC system. To develop this task, four different kinds of ANNs are considered, as follows:

1) ANN to detect a fault;
2) ANN to identify the fault section;
3) ANN to classify a fault at the rectifier substation;
4) ANN to classify a fault at the inverter substation.

Firstly, the algorithm's performance is evaluated regarding each ANN operating separately. This will be followed by a discussion on combining the ANN outputs with logic gates to extend the algorithm's application. Fig. 3 shows the ANNs used in this work, highlighting that all the ANNs take the same input signals and have the same three layer topology, with the exception of the output layer: 100–20–(1, 3 or 7).

A sampling rate of 4 kHz is used to acquire signals at the rectifier substation and five data windows (Va, Vb, Vc, Vd, and Id) of