SSURJET

Sir Syed University Research Journal of Engineering & Technology
2023, Vol. 13, No. 1,
https://doi.org/10.33317/ssurj.548

Time-Frequency Transformation Technique with Various Mother Wavelets for DC Fault Analysis in HVDC Transmission Systems

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Received January 03, 2023; Revised March 01, 2023; Accepted March 09, 2023

Abstract

HVDC transmission has become a cost-effective option for transferring high voltage over greater distances. Protecting an HVDC transmission line is more challenging than protecting an AC transmission line due to its low impedance and absence of zero crossing DC-current. Power electronic devices have finite overload capability, and standard relays are ineffective for HVDC line protection. Heavy current is generated by DC faults in HVDC (T/L), hence it is necessary to treat DC line faults in short, medium, and long HVDC (T/L) systems with different fault resistance. It is crucial to research fault detection methods based on time-frequency analysis by choosing appropriate algorithms using various (MW) methodologies for short, medium, and long HVDC transmissions at various fault resistances in order to protect the HVDC system. In this work, we examine how the length of an HVDC transmission line and fault resistance at both sides (inverter and rectifier) affects the selection of suitable mother wavelets for DC fault, using mean parameter and time-frequency transformation. SimPower System of Matlab is used to evaluate the impact of HVDC transmission line length and fault resistance on the selection of suitable mother wavelets. Simulation results show that Coif3 is an ideal wavelet for fault detection in medium transmission lines at different fault resistances. On the other hand, Rbio3.1 is more suitable for fault detection in long transmission lines at various fault resistances. For short and medium HVDC transmission lines, different mother wavelets were found to be suitable at different fault resistances. Therefore, it is essential to carefully consider the specific characteristics of the transmission line and the fault scenario when selecting a mother wavelet for accurate fault location.

Index Terms: *Converter, Inverter, Rectifier, Time-Frequency Analysis, Wavelets.*

I. INTRODUCTION

It is essential that the electrical power system function continuously and reliably. Power transmission lines must be protected in order to preserve the smooth flow of electricity from generation to transmission to the cities. Transmission line protection systems are essential for preventing short circuits, unusual events, and other disruptions from harming the system and its constituent parts. In order to minimize service interruption, these protective mechanisms are built to swiftly separate the problematic line from the rest of the network [1]. However, due to its high charging current of cable capacitance, i.e., increased losses, lack of asynchronous operation, higher volume of conductors, difficulty in controlling power flow, the requirement for reactive power compensation, skin and Ferranti effects, the High Voltage Alternating Current (HVAC) may not be appropriate for long-distance power transmission [2].

For these shortcomings in HVAC transmission, the use of High Voltage Direct Current (HVDC) transmission has grown dramatically, and DC transmission has evolved into a cost-effective option for transferring high voltage over greater distances. Securing an HVDC transmission line is much more challenging than securing an AC transmission line due to its low impedance and lack of zero crossing of DC current. Standard relays are useless for protecting DC lines from overloads, and power electronic devices offer minimal overload capacity [3]. Many faults, including AC faults, internal converter faults, and DC faults, can affect high-voltage direct current systems. These problems may be brought on by insulation failure brought on by lightning, switching, and short circuits.

Symmetric and asymmetric faults are both possible on the AC side. Internal converter problems include flashover, DC link capacitor failure, and device misfire/fire-through. The Line-to-line (L-L), positive/negative line-to-ground (L-G), and double line-to-ground (2-L-G) faults are the three types of DC faults. The fast rising time, high peak, and continuous fault current of DC faults in a Thyristor-based DC system make them particularly problematic. As a result, the protection of these systems from DC failures has received a lot of attention. Line-to-ground faults are common and are primarily caused by the HVDC system's grounding. Therefore, in case, fault resistance and transmission line length should not be overlooked because it has a significant impact on system reaction [4].

In this proposed work, the effects of DC transmission line length and fault resistance are investigated by utilizing time-frequency transformation using different mother wavelets in case of DC fault on both sides (Inverter and Rectifier) of the high-voltage direct current transmission line using the SimPower System of Matlab.

II. LITERATURE REVIEW

Creating a protection strategy for a multi-terminal VSC-based HVDC system is complicated. However, numerous methods for DC fault detection, identification, and isolation have been developed, including both Current Source Converter (CSC) and Voltage Source Converters (VSC)-based HVDC transmission lines with two-terminal and multi-terminal network architectures [4].

The authors researched to create a model that uses the wavelet transform and ANN algorithm, a self-learning technique, to locate faults in any High Voltage DC transmission line. Data from the built model is applied to the wavelet transform for various fault locations that varied by 1KM [5]. The simulation's findings demonstrate that the most mother Wavelet Transform (WT) for detecting DC faults, symmetrical and asymmetrical faults happen at the 6^{th} level of decomposition of fault signal based on standard deviation. This is done by the use of MATLAB/Simulink software, a straightforward time-frequency analysis method for locating HVDC faults [6]. ANN and WT to develop an accurate plan for predicting the location of a fault in a bipolar Current Source Converter (CSC) based HVDC transmission system. Their suggested algorithm uses the extracted attributes of the DC voltage, current signals, and AC sinusoidal voltage produced at both poles of the rectifier end of the line [7].

The first-level approximation and the detailed discrete wavelet transform coefficients of current at both ends can be utilized to evaluate the location of faults. The three-phase transmission lines were simulated using MATLAB. This technique is tested with a variety of fault types and locations. Fault location in three-phase transmission lines can be evaluated according to simulation results [8]. Researchers employ the Wavelet transform to find faults and specify the problematic phase in a three-phase DC transmission line with series capacitor compensation. Issues with three-phase transmission line protection schemes are caused by series capacitor compensation [9]. To demonstrate the effectiveness of the suggested strategy, researchers created a decentralized fault localization in the DC link using the harmonic analysis of voltage and time domain simulations performed in the PSCAD software [10]. The authors applied the Discrete Wavelet Transform (DWT) to identify and classify the faults on HVDC transmission lines to provide a solution for fault classification and detection of overhead high-voltage DC transmission lines. The Norm's value is compared to the system's threshold values [11]. Researchers used the wavelet transform to provide a unique fault identification method in high-voltage transmission lines during power swing situations. The idea of temporal duration, or the existence of a transient period, is used to distinguish between non-fault and fault transient cases, such as line switching, capacitors, and loads in an arc furnace. The devised method is demonstrated to be reliable for various fault types, fault inception angles, fault locations, and fault resistance. [12]. Researchers give a thorough analysis that provides the best parameter estimation for the DWT used to detect series arc faults in the home AC power network. The effectiveness of arc fault detection is significantly influenced by the selection of these three factors, such as choice of mother wavelet, level of decomposition, and sampling frequency. Additionally, a frequency range with the best arc fault detection performance is found for each evaluated load [13]. Researchers looked into using the DWT to find DC faults in HVDC systems. A method is proposed to select the mother wavelet suitable for DC faults according to the degree of correlation with the fault mode and the time delay. Using the PSCAD/EMTDC software, a multi-terminal HVDC system is subjected to wavelet analysis. To illustrate the problem with window size and noise, the wavelet transform is further contrasted with the short-time Fourier transform [14]. The authors conducted a thorough investigation and analysis to look at a method for locating the defect in a long HVDC transmission line, say up to 1000 km in length. The researchers suggested combining two approaches: the ‘Wavelet Transform’ is one method, and the ‘Travelling Wave Principle’ is the other [15]. The authors look into the accuracy of fault location in a 2400 km overhead HVDC line and a 300 km underground cable HVDC line using the two-terminal traveling wave approach. Compared to the widely used discrete wavelet transform-based technique, adopting continuous wavelet transform (CWT) for detecting the arrival time of moving waves indicates superior accuracy [16]. The issue was solved by researchers utilizing the wavelet transform to determine the type of problems in an HVDC system (WT) [17]. By using the wavelet transform, an HVDC system's fault types can be identified (WT). The system claims to achieve the desired outcome by identifying, classifying, and locating each of the ten potential problems in the power system's transmission line [18]. By simulating the HVDC system for several faults, researchers presented the approach using wavelet transforms for identifying HVDC transmission line defects. The simulation results demonstrate that the wavelet technique is applied to give a more reliable solution for fault detection and a solid foundation for the new HVDC line protection scheme [19]. The authors conducted a study on the use of wavelet transform for identifying, categorizing, and localizing transmission line faults. The suggested algorithm is evaluated for various fault locations, fault types, incidence angles, fault impedances, and incidence angles. The algorithm has been proven effective and efficient at identifying, categorizing, and locating problems [20]. A TW-based technique for MV and LV DC micro-grid quick-tripping protection is presented in this paper. In the suggested approach, authors used to determine the high-frequency components of DC fault currents [21]. Research suggested transmission line fault detection, classification, and location, a multifunctional protection methodology combining DWT-MRA and traveling waves [22]. Examine different techniques for detecting, locating, and isolating DC faults in VSC and CSC-based HVDC transmission systems in two-terminal and multi-terminal configurations [23]. Bipolar CSC-based high voltage DC transmission line high-speed fault protection was examined using the bagged tree ensemble classifier scheme in conjunction with the wavelet transform. [24]. Proposed a method by authors to locate DC arc faults in VSC-HVDC transmission lines.

PMU also employs advanced signal processing approaches, such as the wavelet transform, to extract crucial fault signal features from both sides of the line [25]. Researchers did a quick summary of the various approaches for analyzing power system issues. It also shows that classic fault analysis approaches like Artificial Neural Networks (ANN), Wavelet Transforms (WT), and Fuzzy Inference Systems (FIS) have a big impact [26]. Proposed by authors an MMC-HVDC transmission line transient current protection technique. The MMC test model has been validated under various operating settings and fault scenarios [27]. The authors suggested a time-frequency analysis technique for identifying faults in HVDC transmission lines using Matlab software. This work identifies four different types of faults [28]. This research has analyzed fault voltage and current signals using variance, standard deviation, and range parameters to select the best mother wavelets for various transient states. According to this work in fault detection, it's more reliable to use multiple mother wavelets instead of just one [29], and [30].

III. PROPOSED RESEARCH METHODOLOGY

The following steps are involved in analyzing faults in the HVDC transmission line, and the block diagram for the proposed research methodology is shown in figure I:

a) Transforming HVDC transmission line model for DC fault.
b) Generating DC line fault in transmission line and gathering data.
c) Transferring that data to the wavelet analyzer.
d) Apply orthogonal and bi-orthogonal mother wavelets.
e) Analyze detailed coefficients at a suitable level.
f) Calculate the mean of various mother wavelets to analyze their performances.
g) Repeating the same process by changing the DC transmission line length and fault resistances.
h) Comparing results and analyzing any effect of change in DC transmission line length and DC fault resistance.

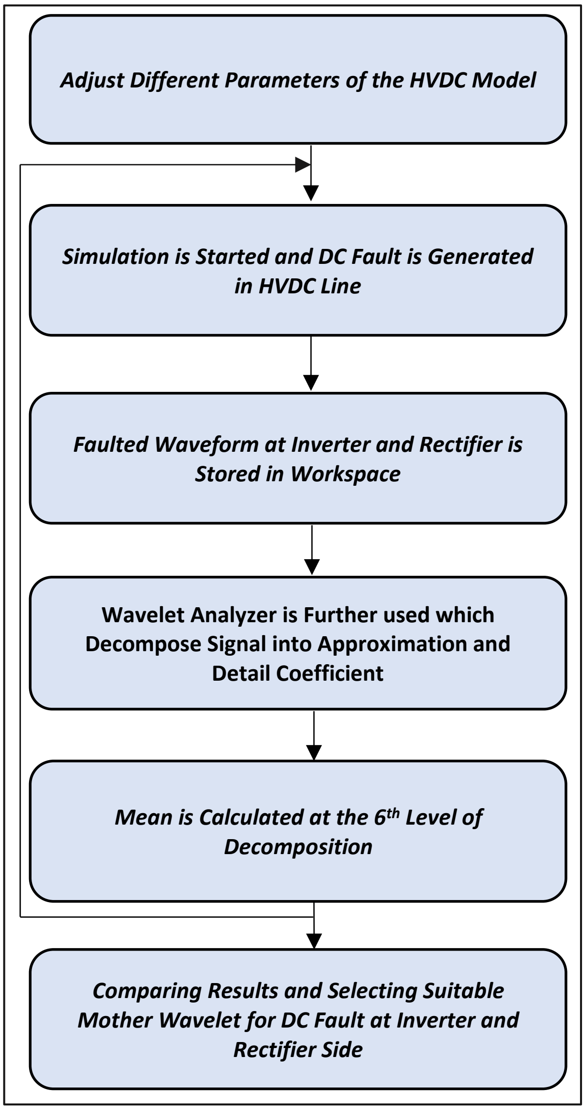

Figure I: Flow Chart based on Research Methodology

IV. HVDC TRANSMISSION LINE MODEL

Figure II, below shows the designed Thyristor-based HVDC model in Matlab SimPower Software.

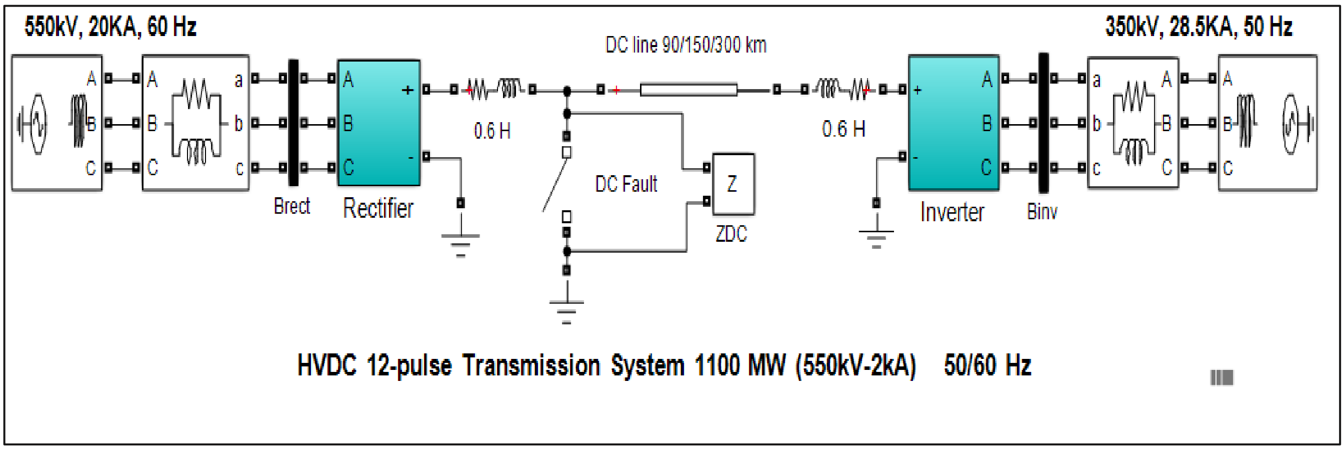

Figure II: HVDC Transmission Line Simulation Model

An 1100 MW (550 KV, 2 KA) DC interconnection is used to transmit power from a 550 KV, 10 KA 60 Hz network to a 350 kV, 28.5 KA 50 Hz. The rectifier and inverter are connected through different transmission line lengths (90 km, 150 km, and 300 km).

V. RESULTS AND DISCUSSIONS

Data is the primary source of information required, so it has to be accurate. For this research, data from transmission line parameters were collected from the simulation of an HVDC transmission line model for DC line fault at 90 km, 150 km, and 300 km.

The following data sets are obtained:

- Rectifier Side DC Voltage.
- Inverter Side DC Voltage.

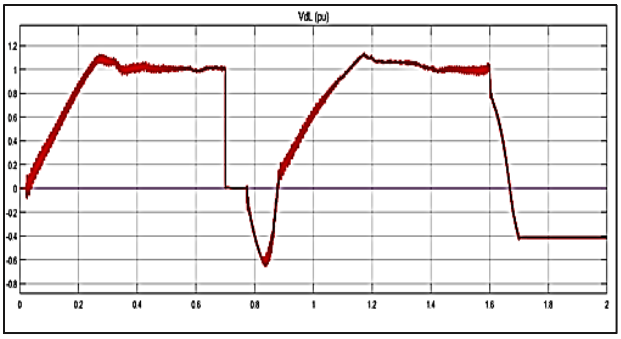

Figure III: DC Fault at Rectifier Side

Figure III shows the DC line to the ground fault at the rectifier side. The fault starts at 0.7 seconds and ends at 0.75 seconds.

Table I: Suitable Mother Wavelets at Different Fault Resistance and Transmission Line Length

Fault Resistance	Transmission line length 90 km	Transmission line length 150 km	Transmission line length 300 km
1 Ohm	Rbio 3.1	Coif 3	Sym 7
3 Ohm	Rbio 3.9	Coif 3	Coif 4
5 Ohm	Rbio 3.5	Coif 3	Bior 3.1

The above table i.e., table I shows various suitable mother wavelets for detecting DC faults by analyzing the rectifier side voltage of the HVDC transmission line. In a 90 km transmission line, rbio3.1 is suitable for a 1 Ohm fault resistance, rbio3.9 is suitable for a 3 Ohm fault resistance, and rbio3.5 is suitable for a 5 Ohm fault resistance. In a 150 km transmission line, coif3 is suitable for both a 1 Ohm and a 3 Ohm fault resistance. In a 300 km transmission line, sym7 is suitable for a 1 Ohm fault resistance, coif4 is suitable for a 3 Ohm fault resistance, and bior3.1 is suitable for a 5 Ohm fault resistance.

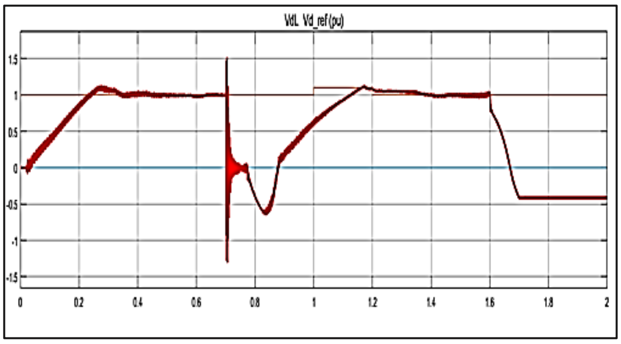

Figure IV: DC Fault at Inverter Side

Figure IV shows the DC line to the ground fault at the inverter side. Fault starts at 0.7s and ends at 0.75s.

Table II: Suitable Mother Wavelets at Different Fault Resistance and Transmission Line Lengths.

Fault Resistance	Transmission line length 90 km	Transmission line length 150 km	Transmission line length 300 km
1 Ohm	Rbio3.9	Sym7	Rbio3.1
3 Ohm	Rbio 3.9	Coif 4	Rbio3.1
5 Ohm	Haar, Db1, Bior1.1,Rbio1.1	Coif 4	Rbio3.1

Table II. shows various suitable mother wavelets for detecting DC faults by analyzing the inverter side voltage of HVDC transmission lines. At 1 Ohm fault resistance, in a 90 km line, the suitable mother wavelet is rbio3.9, at 3 Ohm fault resistance, the suitable wavelet is still rbio3.9, at 5 Ohm fault resistance, the wavelet changes to db1, haar, bior1.1, rbio1.1. For a 150 km line, the suitable wavelet is sym7 at 1 Ohm and coif4 at 3 and 5 Ohm respectively. For a 300 km line, the wavelet is rbio3.1 for all three fault resistances.

VI. CONCLUSION

The research will contribute to the development of an effective fault detection and protection scheme for HVDC transmission lines, which will ensure the reliability and stability of the power system. The use of suitable mother wavelets for fault detection will result in accurate and fast fault detection, reducing downtime and improving the system's performance. The software-based approach of this study will be useful for researchers and consumers alike in the future. This research utilizes the SimPower System of Matlab to simulate various fault scenarios in HVDC transmission lines of different lengths and fault resistances. The study's findings provide new insights into the selection of suitable mother wavelets for fault detection in HVDC transmission lines of different lengths and fault resistances, which can improve the accuracy and efficiency of fault detection systems. Paper results show that the suitable mother wavelet for detecting DC fault at the rectifier side in the long transmission line is coif3; there was no effect due to fault resistance on the mother wavelet. And at the inverter side, Rbio3.1 is a suitable mother wavelet whether the fault resistance is smaller or higher. So for designing a protection scheme for the HVDC transmission line, researchers must be careful whether the fault detection system has been installed at the rectifier or inverter side. The research is limited to software-based simulations using the SimPower System of Matlab. While the results provide valuable insights into the selection of suitable mother wavelets for fault detection in HVDC transmission lines, further testing and validation are necessary before implementing the findings in practical applications.

Acknowledgment

The authors would like to thank almighty Allah first and then the management of Quaid-e-Awam University Nawabshah, Pakistan, for their support and their assistance throughout this study.

Authors Contributions

Both authors jointly took the responsibility of conducting this research study and their contribution was equal.

Conflict of Interest

The authors declare no conflict of interest and confirm that this work is original and not plagiarized from any other source. The information obtained from all of the sources is properly recognized and cited below.

Data Availability Statement

The testing data is available in this paper.

Funding

This research received no external funding.

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