SSURJET

Sir Syed University Research Journal of Engineering & Technology
2023, Vol. 13, No. 1,
https://doi.org/10.33317/ssurj.539

Application of Time-Frequency Analysis with Selection of Suitable Mother Wavelets for Transient States of HVDC Transmission Lines

Muhammad Tarique Chachar[1*], Aslam Pervez Memon[1], and Jamshed Ahmed Ansari[2]

[1]*Department of Electrical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Pakistan*
[2]*Department of Electrical Engineering, Sukkur Institute of Business Administration University, Sukkur, Pakistan*

**Correspondence Author: Muhammad Tarique Chachar (19mpm04@quest.edu.pk)*

Received October 31, 2022; Revised December 09, 2022; Accepted December 23, 2022

Abstract

Recent developments in power semiconductor devices have made High Voltage Direct Current (HVDC) transmission systems the most crucial technology for future power systems. Today several HVDC projects have been commissioned around the world. The primary concern for such an advanced HVDC grid is to follow standard grid codes to maintain the safety and stability of the electrical equipment during transient and dynamic circumstances. Although the HVDC system has been recognized as the most prominent technology to transmit electric power, some issues must be addressed, such as selective and quick detection of faults. For selective fault detection, it is essential to look into the several fault detection strategies that fortify the HVDC system with time-frequency signal processing techniques. This research uses a time frequency-based method to identify the different HVDC transmission line faults. The most suitable mother wavelet for various transient states is selected by analyzing fault voltage and current signals based on variance, standard deviation, and range parameters. An experimental setup of a thyristor-based HVDC transmission system has been developed in the MATLAB/Simulink environment, and multiple fault scenarios have been analyzed. The simulation outcomes reveal that the most effective mother wavelet for detecting DC line, symmetrical and unsymmetrical faults occurs at the 6th level of fault signal decomposition. By examining current and voltage signals, our work has determined the best mother wavelet for various faults. Using more than one mother wavelet to detect faults is more reliable than using a single mother wavelet to detect all faults. Additionally, it has been noted that each fault's voltage and current signals have two distinct mother wavelets.

Index Terms: *DC Line Fault, HVDC Transmission Line, Three-Phase Transients, Time-Frequency Analysis, Wavelet Transformation.*

I. INTRODUCTION

Due to the rising electricity demand, conventional and non-conventional energy resource interconnections are growing daily [1]. This requires transmitting electric power over long distances with asynchronous grid ties. The HVDC systems easily accomplish such requirements. Compared to High Voltage Alternating Current (HVAC) systems, HVDC systems possess numerous advantages, such as improved reliability, reduced transmission losses, and lower transmission costs. With the recent development of power semiconductor devices, the overall efficiency of the HVDC system has been improved [2], and [3]. The present-day HVDC transmission technology is a reliable option for transmitting electrical power. However, such systems are susceptible to electrical faults [4]. A longer duration of faults in an HVDC system can cause damage to the DC cable and converter itself [5]. Therefore, it is critical to diagnose the type of fault as soon as possible. The possible faults in an HVDC system are three-phase symmetrical and unsymmetrical transients on the AC side of the converter station and pole-to-pole and pole-to-ground faults on the DC side of the converter station [6].

It is essential to consider the various fault detection systems that use time-frequency signal processing techniques to secure the HVDC system. To overcome the different transient conditions in an HVDC system, a quick, selective, and practical approach with time-frequency characteristics is required [7], and [8]. A criterion that depends on time-frequency characteristics is optimal since fault transients are time and frequency-based signals [9]. Wavelet transform is mainly used to analyze the two parameters, i.e., the DC voltage and the DC current [10]. Wavelet transform utilizes various types of families as a basis function, whereas Short Time Fourier Transform (STFT) utilizes sinusoidal functions. The wavelet families comprise functions known as the father wavelet and mother wavelet. The dilation and shifting can alter wavelets, resulting in numerous daughter wavelet functions. STFT can only be used in a fixed window. Therefore, better frequency resolution is produced with a broader time frame at the expense of time resolution and vice versa. Since the wavelet functions are more flexible, in response to the dynamic nature of the signal, they may automatically modify the window size [11]. This feature, which offers a time-frequency dependent Multi-Resolution

Analysis (MRA), is implemented using various low-pass and high-pass filters. MRA helps to detect the change in voltage, current, and frequency, which occurs during faulty conditions for different time durations [12].

Authors examine a wide range of direct line transient characteristics, which include line inside and out, lightning strokes, noise interference, and line earthing with high resistance [13]. Many findings indicate that travelling wave protection has effective ascending action and anti-jamming properties. Researchers discuss a wavelet analysis-based technique for detecting faults in HVAC and HVDC systems, by detecting differences using wavelet modulus maxima [14]. Wavelet transform is utilized for fault detection, while ANN is employed for classification. Detection methods for HVDC converter faults like commutation failure, backfire, fire-through, and misfire is discussed in detail [15]. A real-time fault classification technique for protecting transmission systems is proposed by researchers [16]. This method uses well-estimated/calculated spectral energy. The neural network scheme has been proposed after implementing it on various faults. A direct approach for identifying the faults in the HVDC transmission line using ANN has been proposed [17]. The position of the fault is determined using single-end AC RMS voltage and DC voltage and current. The characterization of the system fault is determined using the DC voltage amplitude fluctuation range [18]. The wavelet analysis technique is combined with ANN to identify the system fault. The Mallet algorithm is used to recognize DC line and 3-phase grounding faults in a dynamic HVDC system [19]. The authors have introduced a method that detects faults inside or outside the protective zone based on signals with high frequency [20]. An algorithm is proposed which improves the fault location accuracy, irrespective of the transition resistance [21]. Furthermore, according to the researchers, it eliminates the need to artificially identify the moving wavefront, making fault position automation simple to be implemented. A DC fault detection technique is proposed for the pole-to-pole and pole-to-earth, and numerical case studies were used to test this fault detection algorithm [22]. This article discusses the consequences of different failures in the VSC-HVDC system. The fault currents are detected using the wavelet transform [23]. Researchers propose a protective system for the HVDC transmission line. The suggested method is tested on obtained data from fault simulation performed on EMTDC/PSCAD and from actual unanticipated tripping incidents of conventional TWP [24]. The wavelet-based technique is used to identify faults in the HVDC system. The results presented show higher accuracy for fault location detection, which is about 99.3% [25]. The different overcurrent patterns are investigated for various fault and load change cases. In this scheme, the simulation is performed on PSCAD, and the results are imported to MATLAB for further processing [26]. Authors have proposed a time-frequency analysis technique for identifying faults using MATLAB software. Four types of faults are detected in this work [27]. The authors have compared the efficiency of two fault detection methods with the wavelet transform. The first method is the capacitive discharge technique, a time-domain analysis of the DC-link capacitor discharge. The second method employs a frequency domain-based short-time Fourier transform to examine the fault current's high-frequency components statistically [28]. A feature extraction technique for fault detection in an HVDC system is proposed [29]. Data is mapped into the wavelet domain of the distorted signal as the initial step of the feature extraction procedure. In the second step, those distorted energy signals at various resolution levels are used to characterize different faults. Based on a study, a TW-based strategy for MV and LV DC microgrid rapid tripping protection is provided. The proposed approach calculates the high-frequency components of DC fault currents using Multi-Resolution Analysis (MRA) [30]. Another study suggests a multifunctional protection methodology combining Discrete Wavelet Transform-Multi-Resolution Analysis (DWT-MRA) and travelling waves for transmission line fault detection, classification, and locality [31]. The suggested method employs d-q transformed travelling waves to detect the fault and uses the timing of the first travelling wave occurrence at both ends of the line to find the fault. The research analyzes the various methods for DC fault detection, localization, and isolation in CSC and VSC-based HVDC transmission systems in two-terminal and multi-terminal configurations [32]. Research conducted that focused on, a feature reconstruction method for bipolar CSC-based HVDC transmission line high-speed fault protection uses the bagged tree ensemble classifier algorithm, and the wavelet transforms [33]. Research suggests a method for finding DC arc faults in VSC-HVDC transmission lines [34]. In addition, PMU uses the wavelet transform using sophisticated signal processing techniques to extract significant fault signal features from both sides of the line. The article provides a brief and comprehensive overview of the various methodologies used to analyze power system faults and it demonstrates that traditional methods such as ANN, WT, and FIS significantly affect fault analysis techniques [35]. Another research designs a VSC-HVDC system with voltage and current controllers and properly models a transmission line. An HVDC transmission system has many fault types, including PP, PG, and NG faults, which are built and simulated. Researchers have used DWT and Support Vector Machine (SVM) for fault detection and classification, by using the db3 mother wavelet [36]. Research work conducted for the detection of the line-to-line fault and the series arc fault, respectively, the discrete wavelet transform and derivative of teager energy have been proposed, and rbio3.1 mother wavelet is utilized to detect a line-to-line fault [37]. With the help of the Selective Particle Swarm Optimization (SPSO) algorithm, the specified model is resolved for a radial distribution system with a non-uniformly distributed load [38]. At the system's nodes, the desired technique improves the voltage profile while reducing power loss. For the simulation, MATLAB is used, and the Electrical Transient Analysis Program (ETAP) also validates the results. The findings demonstrate that installing optimally sized DGs at ideal system nodes results in a significant reduction in power loss and an enhanced voltage profile at the network's nodes. In an article, the network reconfiguration research for transmission networks is examined, along with unit skeleton networks, restoration paths, and startup sequences. Also, it discusses optimization models, optimization methodologies, and CNT-based indices. Additionally, real-world difficulties, technical problems (transient problems) that arise during the transmission system's network reconfiguration, and business practices are presented and thoroughly discussed [39].

This paper proposes a highly efficient time-frequency analysis wavelet technique with suitable mother wavelets for detecting transients in the HVDC transmission system. The Multi-Resolution Analysis (MRA) is used for the 6th-level decomposition of the faulty signal to determine the coefficients of the current and voltage signals. Moreover, the variance, standard deviation, and range of decomposed detail coefficients at the 6th level are determined for different transient conditions. Finally, the experimental results are carried out in a simulation environment. The rest of the paper is organized as Section II presents the HVDC transmission line model, and Section III the research methodology. In Section IV, results for the proposed algorithm are discussed in detail, and Section V concludes the paper's outcomes.

II. PROPOSED RESEARCH METHODOLOGY

The following steps are involved in analyzing faults in the HVDC transmission line:

1. Modify the existing HVDC transmission line model for different fault conditions.
2. Generate various fault conditions.
3. Save faulty current and voltage signals.
4. Transfer the data to the wavelet analyzer.
5. Apply mother wavelets (haar, db1 to db10, sym2 to sym8, coif1 to coif5, fk4 to fk22, bior1.1 to bior6.8, rbio1.1 to rbio6.8, and dmey) to the fault signals at a suitable level of decomposition.
6. Calculate the variance, Standard Deviation (SD), and range of various mother wavelets to analyze their performance.
7. Suggest the most suitable mother wavelet for each fault.

The block diagram for the proposed research methodology is shown in figure I.

A. Wavelet Transform

Wavelets are a function created by scaling and translating a single function, called the analyzing wavelet or mother wavelet. Wavelet transform can evaluate both the rapid transitions of signals and the location of their existence simultaneously since it can localize both time and frequency. The mathematical relationship for wavelet is defined as [40]:

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{a}}\Psi\left(\frac{t-b}{a}\right) \qquad (1)$$

Here:
a and b are the dilation (Scale) and translation (Position) variables.

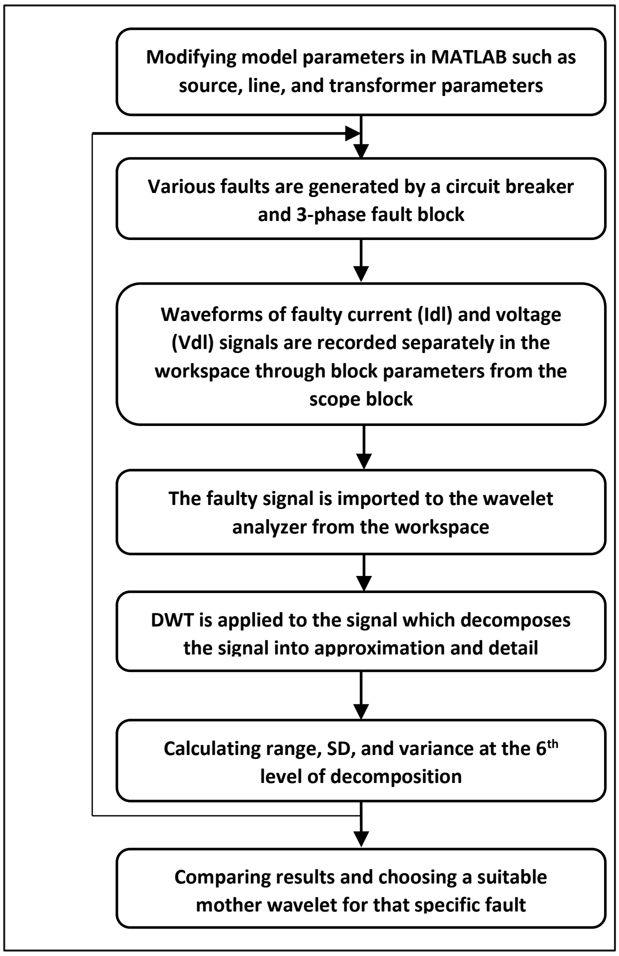


Figure I: Flow Chart for Proposed Methodology

B. Discrete Wavelet Transform and Multi-Resolution Analysis

Discrete Wavelet Transform (DWT) is a widely studied algorithm in the latest mathematical approaches as an effective platform for non-stationary signal processing time-frequency analysis.

The DWT is defined as [41]:

$$DWT(j,k) = \frac{1}{\sqrt{2j}}\int_{-\infty}^{\infty} x_t\psi * \left(\frac{t-k2^j}{2^j}\right)dt \qquad (2)$$

Where:
$\psi(t)$ = mother wavelet,
$*$ = Complex Conjugate,
$j(j \in R)$= Scale Parameter (which determines the wavelet length and oscillation frequency),
$k(k \in R)$= Translation Parameter (which determines the wavelet function's position on the time axis).

DWT's scale and translation parameters serve as the foundation for MRA, allowing MRA to provide high resolution at high and low frequencies. DWT-based MRA decomposes the original signal into the low-frequency approximate and high-frequency detailed signal [41]. The original signal can be expressed as [42]:

$$\left\{ \begin{array}{l} x(t) = \sum_{k=0}^{2^{r-J}-1} a_{J,k}2^{-\frac{J}{2}}\phi(2^{-J}t-k) + \\ \qquad \sum_{j=1}^{J}\sum_{k=0}^{2^{Y-J}-1} d_{j,k}2^{-\frac{j}{2}}\psi(2^{-j}t-k) \end{array} \right. \qquad (3)$$

Where:
$\phi_{j,k}(t)$= Scaling Function,
$aj,$ = Approximate Coefficients,
$\psi_{j,k}(t)$= Wavelet Function,
$dj,$ = Detailed Coefficients,
N = Maximum Layer of Decomposition,
J = Current Layer of Decomposition.

The approximate is a signal composed of approximate coefficients and a scaling function. The detailed function is composed of the detailed coefficients and wavelet function. The wavelet function is related to the high pass filter coefficient, and the scaling function is associated with the low pass filter coefficient.

III. THE HVDC TRANSMISSION SYSTEM

In this research work, an HVDC transmission line model is simulated to identify the different transient conditions. The block diagram of the simulated HVDC system is shown in figure II. The 1100 MW (550 KV, 2 KA) DC connection is used to transfer power from a (550 KV, 10 KA) 60 Hz network to a (315 kV, 28 kA) 50 Hz system. The inverter and rectifier stations are modelled as 12-pulse converters which are connected through a 100 Km line in series by two universal bridge blocks.

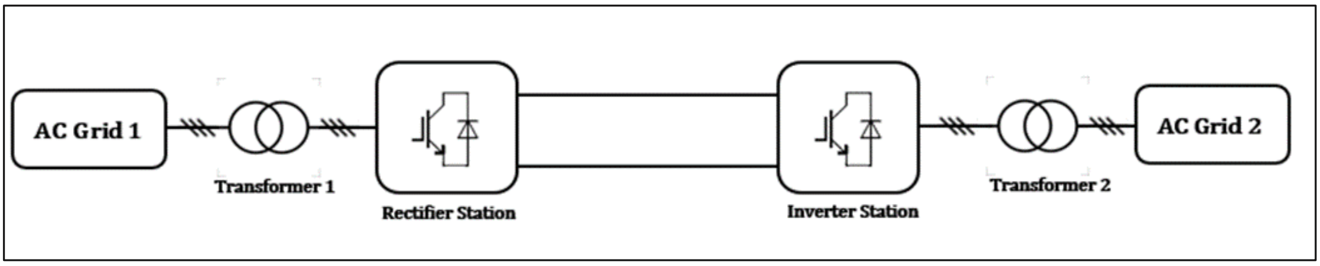


Figure II: Single Line Diagram of 1100 MW HVDC Transmission Line

IV. RESULTS AND DISCUSSION

The following cases are simulated in this proposed study, as shown in table I. Every simulated case is examined based on variance, standard deviation, and range techniques. In the simulated cases, the duration of the fault is kept at 50 milliseconds. Fault resistance in all cases is considered as 0.02 ohm, except DC line fault, which is 1 ohm. A suitable mother wavelet has been proposed for each simulated case to detect the fault.

Table I: Various Fault Cases

Case	Type of Fault
Case 1:	DC Cable Fault (Pole to Ground)
Case 2:	1ϕ to Ground Fault (SLG)
Case 3:	2ϕ to Ground Fault (LLG)
Case 4:	The line to Line Fault (LL)
Case 5:	3ϕ Short Circuit
Case 6:	3ϕ to Ground Fault

A. CASE I: DC Cable Fault

To extract a detailed coefficient for DC line fault, a pole to a ground fault has been simulated in this section. As shown in figure III, the HVDC line voltage V_{dL} falls to zero per unit, and the line current I_{dl} rises to 2.077 per unit compared to the reference I_{dref} current. After fault clearance, the system turns to normal operating conditions. Figure IV compares different mother wavelets through a bar graph representation based on other techniques. From figures IV; (a), (b), and (c), it is quite visible that Db4 has the lowest SD and variance values, coif4 based on range parameters using a voltage signal.

Hence, db4 can extract the DC fault data from the fault signal in the HVDC transmission system by analyzing voltage signals. And by analyzing the current signal rbio3.9 is most suitable based on SD and variance parameters, whereas Db9 is the most suitable MW based on the range parameter.

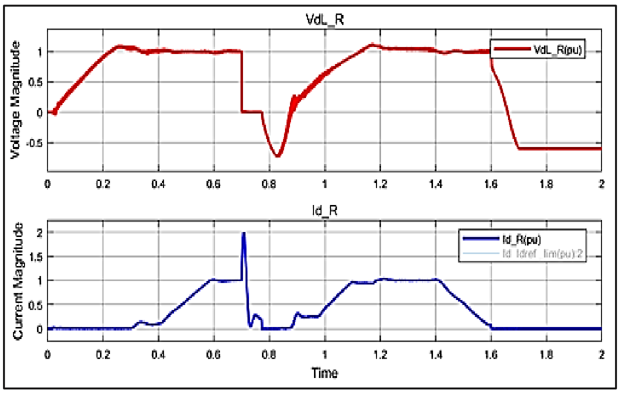
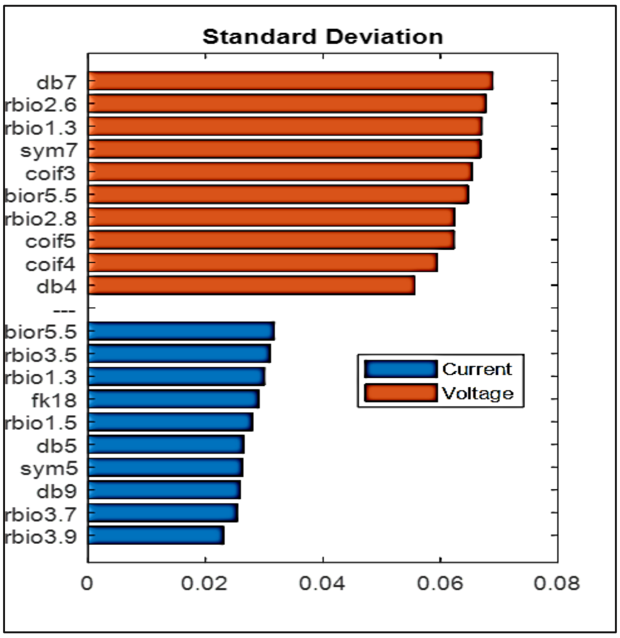
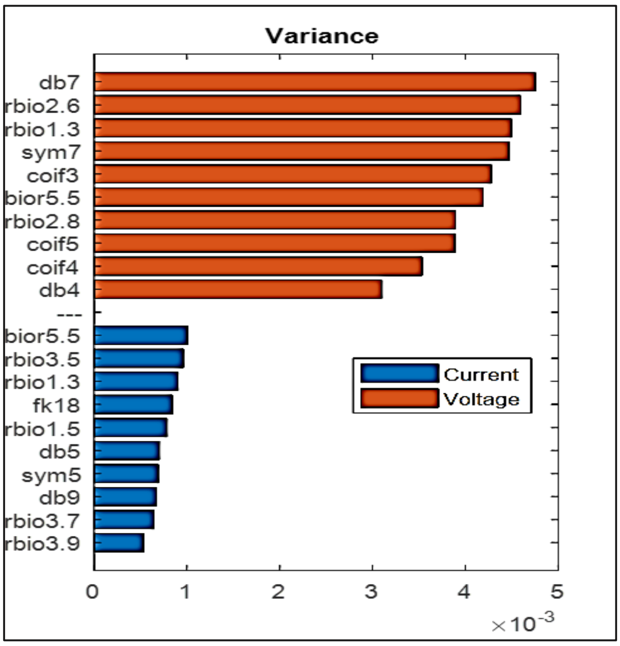


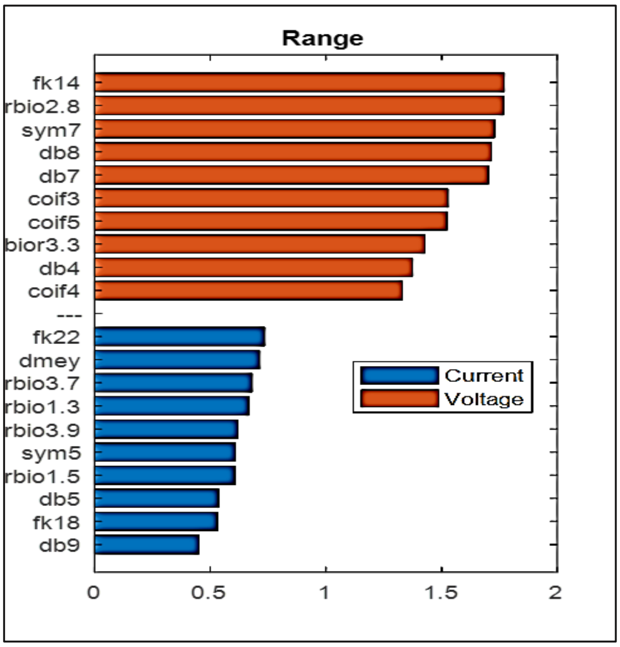
Figure III: Voltage and Current during DC Cable Fault



(a)



(b)



(c)

Figure IV: (a), (b), and (c); Comparison between Mother Wavelets for DC Line Fault

B. CASE II: Single Line to Ground Fault

Figure V, below shows variations in voltage and current when a fault occurs between phase A and ground at the inverter side. Because of the fault, voltage (VdL) drops to -0.349 per unit at 0.72s, and current (Idl) increases to 1.749 per unit at 0.733s with respect to a reference current (Idref). The voltage drop in phase A to ground fault is maximum and rapid as compared to other single phases to ground faults. Current and voltage recover after the fault is cleared. Figure VI shows the variance, Standard Deviation (SD), and range of various mother wavelets for phase A to ground fault's feature extraction. The analysis of signals is shown in figure VI; (a), (b), and (c) based on the SD, Variance, and Range parameters bior5.5 MW has an outstanding capability to extract the detailed coefficients at the 6th level of decomposition by analyzing voltage signal. At the same time, rbio3.9 is the most suitable MW based on all three parameters using the current signal. Hence above-mentioned MWs are most suitable for extracting the SLG fault data from faulty signals in the HVDC transmission system.

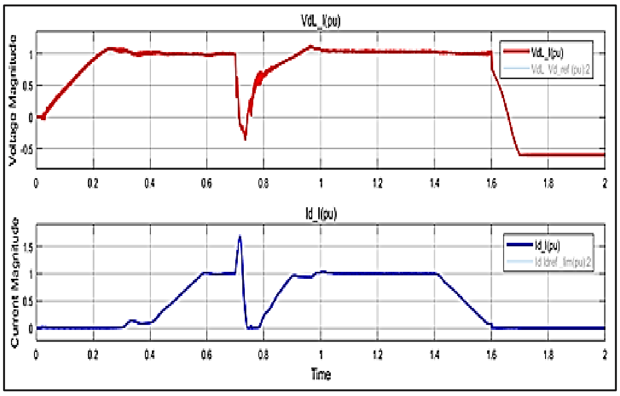
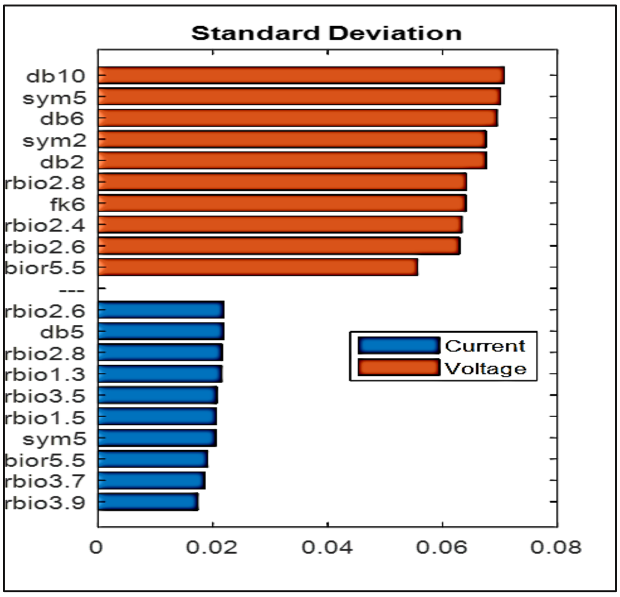
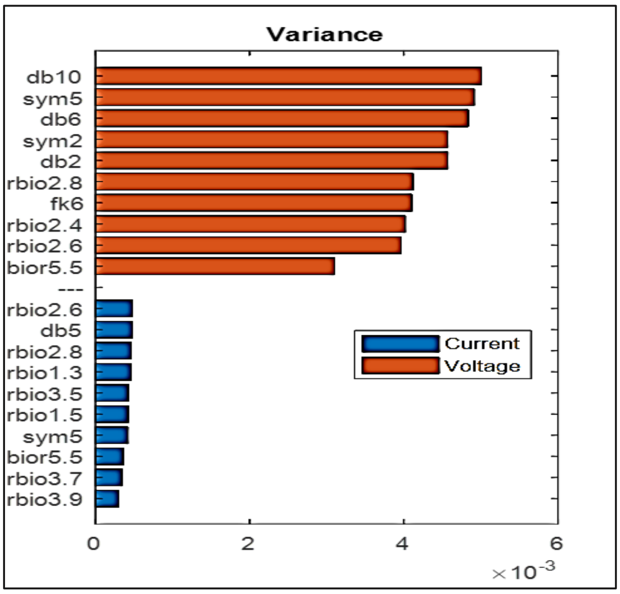


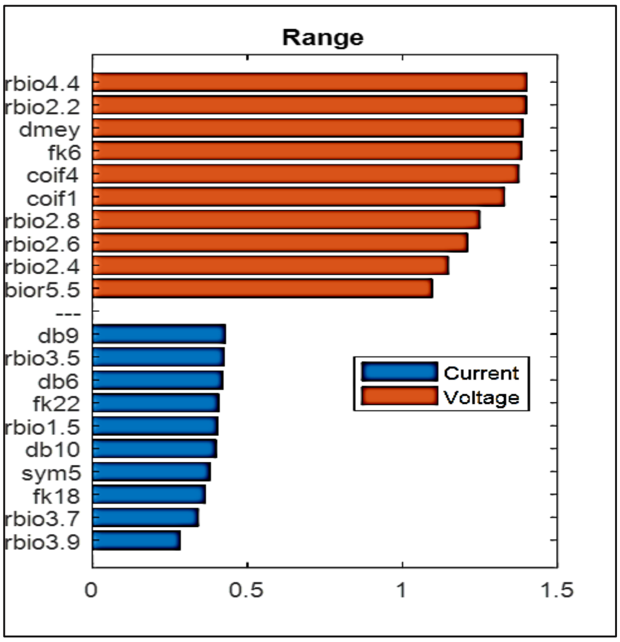
Figure V: Voltage and Current during SLG Fault



(a)



(b)



(c)

Figure VI: (a), (b), and (c); Comparison between Mother Wavelets for SLG Fault

C. *CASE III: Double Line to Ground Fault*

Figure VII shows the voltage (VdL) and current (Idl) of the DC line at the inverter side when phase A and B to ground fault occurs. At the time t = 0.7s, the voltage (VdL) drops and attains a new value of -0.433 per unit at 0.726s. It is the most rapid voltage drop as compared to other SLG faults. During the fault, the current (Idl) increases to 1.973 per unit at 0.709s. The system works properly after fault clearance.

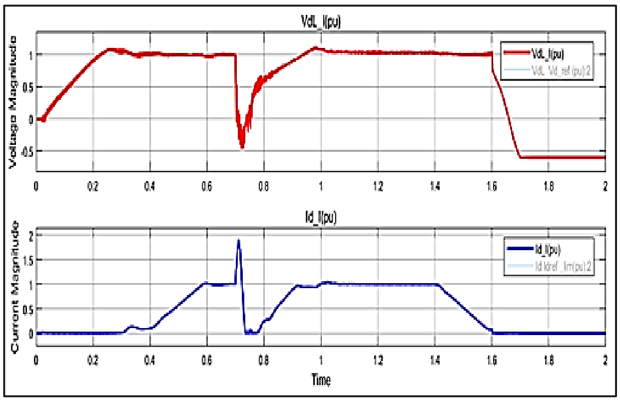
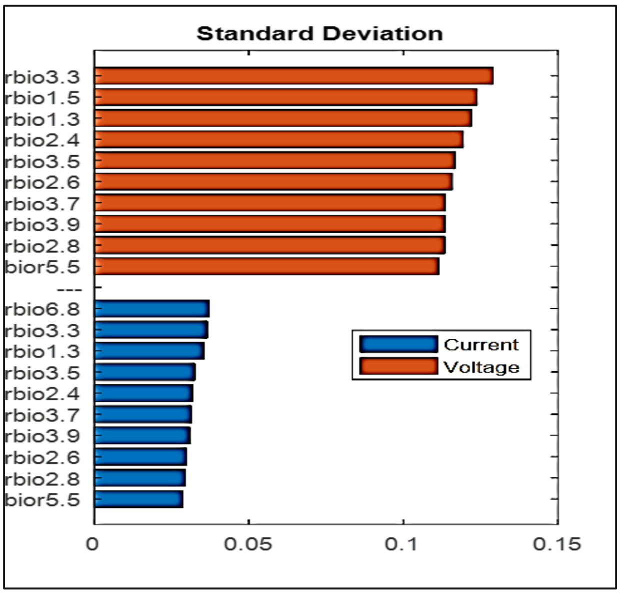


Figure VII: Voltage and Current during LLG Fault

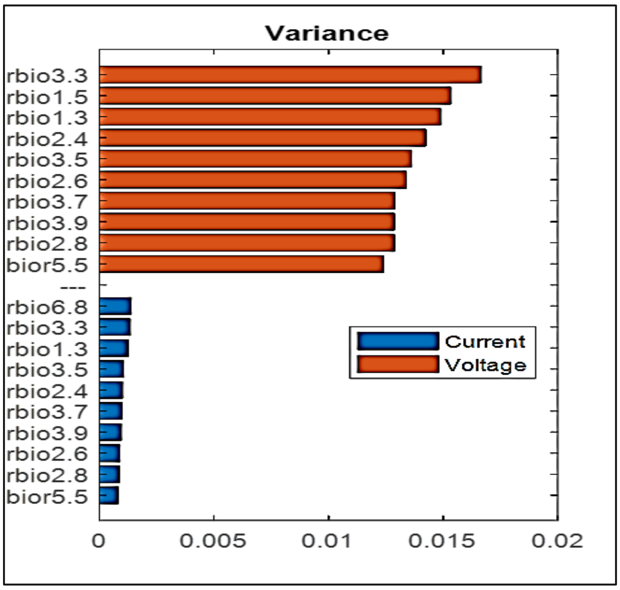
In figure VIII, the variance, SD, and range of all mother wavelets have been compared to select the most suitable mother wavelet for LLG fault.

The bar graph result concludes that the Bior5.5 is the most suitable mother wavelet for LLG fault by analyzing voltage and current signals based on SD and variance techniques as shown in figure VIII; (a), (b), and (c).

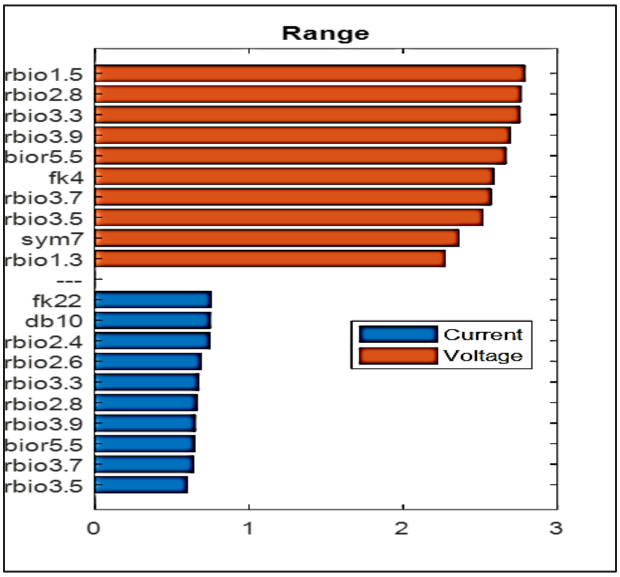
While analyzing voltage signal Rbio1.3 and Rbio3.5 MW by analyzing the current signal is the best mother wavelet to extract the information from the detailed coefficient at level 6 decomposition.



(a)



(b)



(c)

Figure VIII: (a), (b), and (c); Comparison between Mother Wavelets for Phase LLG

D. CASE IV: Line-to-Line Fault

Figure IX shows the HVDC line voltage (VdL) and current (Idl) when the HVDC model is subjected to line-to-line fault on the AC side of its inverter.

It can be observed that the voltage (VdL) drops to -0.342 per unit at 0.724s which is the maximum voltage drop compared to all faults examined in this paper, and the current (Idl) increases to 1.821 per unit. And in this case, the system protection is turned on to secure the HVDC transmission system.

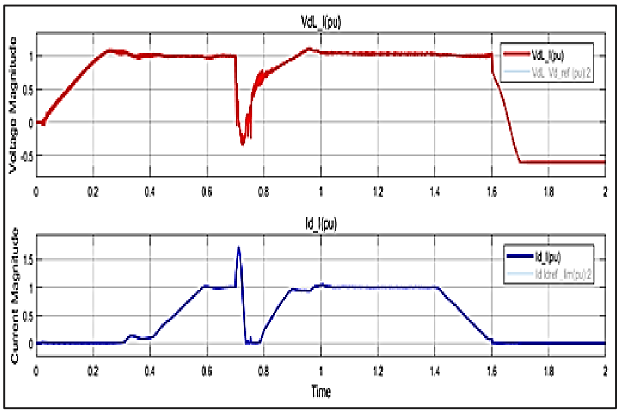
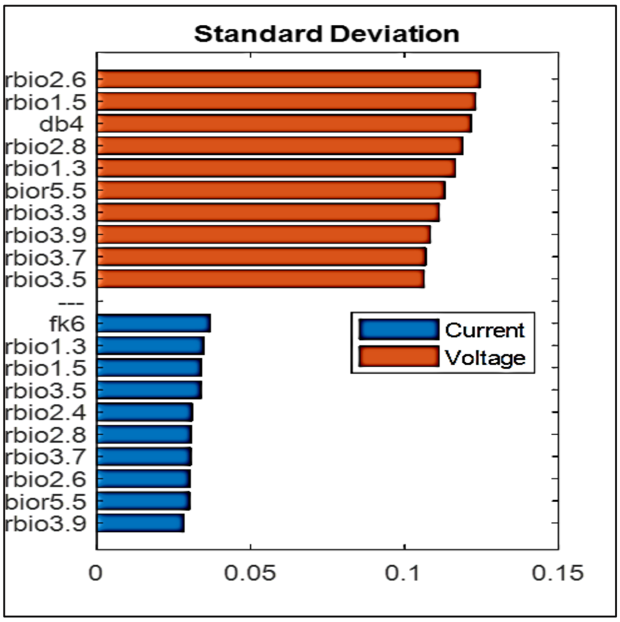


Figure XI: Voltage and Current during Line-to-Line Fault

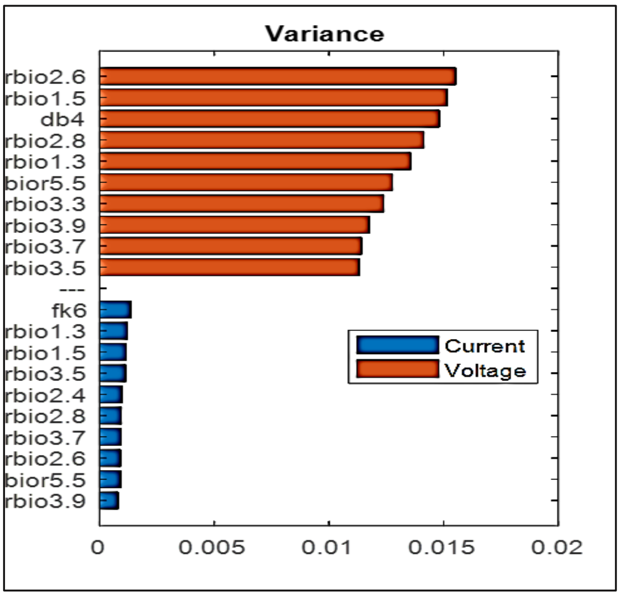
Figure X illustrates the bar graph comparison between all mother wavelets for line-to-line fault based on variance, SD, and range.

Observing the voltage signals as shown in figure X; (a), (b), and (c), it can be witnessed that rbio3.5 is the most suitable mother wavelet for line-to-line fault detection with the lowest values of SD and variance, whereas Rbio3.9 MW based on range technique.

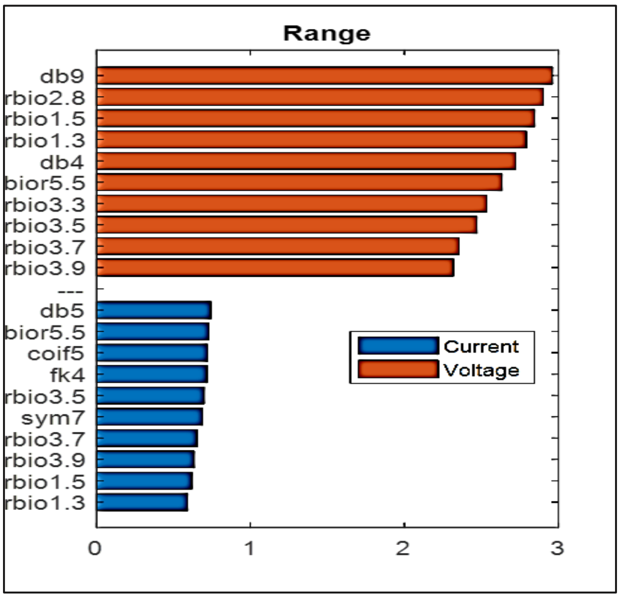
Therefore, Rbio3.9 is considered the best mother wavelet for line-to-line fault extract information from detailed coefficient at level six decomposition for the current signals based on SD and variance and rbio1.3 mother wavelet based on range method.



(a)



(b)



(c)

Figure X: (a), (b), and (c); Comparison between mother wavelets for Line-to-Line Fault

E. CASE V: Three-Phase Short Circuit Fault

In this case, a three-phase short circuit fault is created for 50 milliseconds.

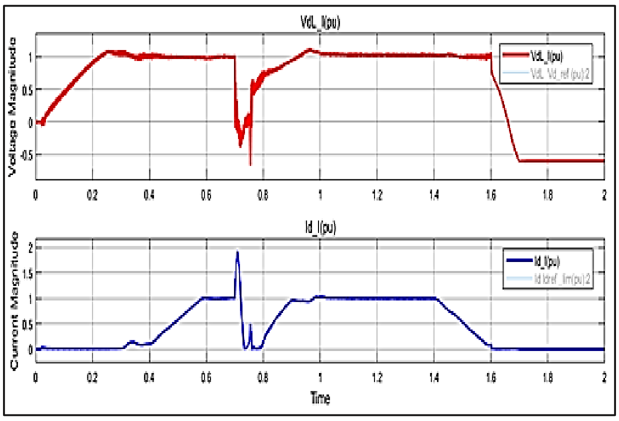


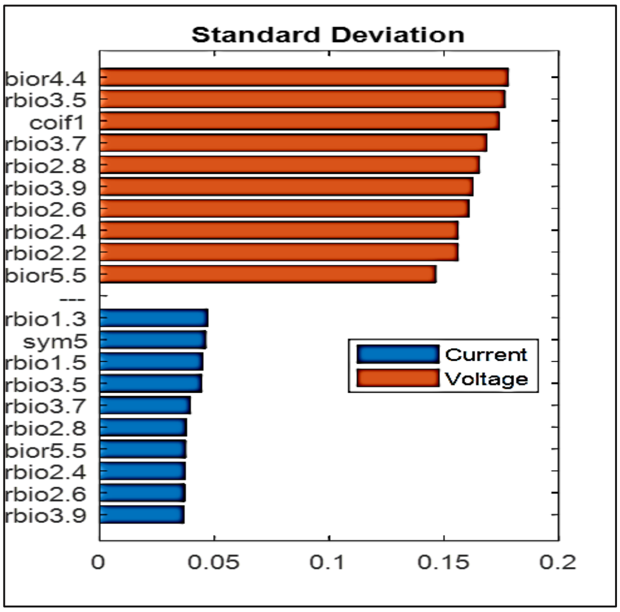
Figure XI: Voltage and Current during Three-Phase Short Circuit Fault

It can be observed from figure XI that the DC line voltage (VdL) drops to -0.667 per unit at 0.755s, and the current (Idl) increases to 1.928 per unit at 0.709s with respect to a reference current. When the protection system is triggered, the system returns to its normal operating condition.

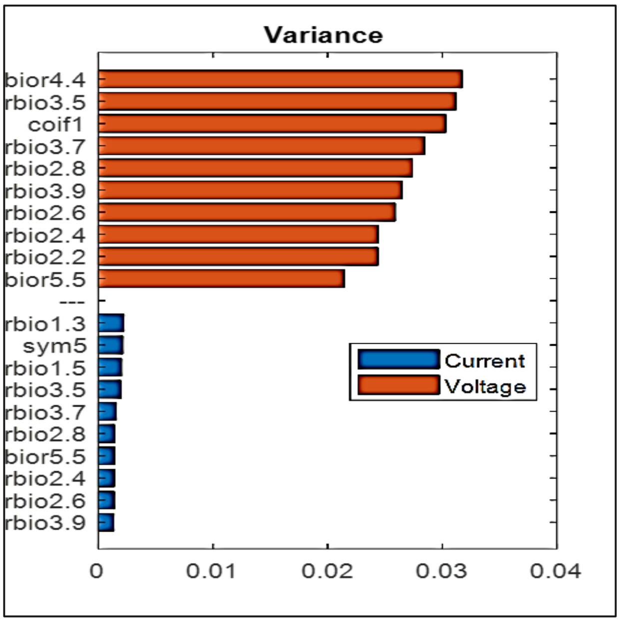
In figure XII, all mother wavelets are arranged to suggest the most suitable mother wavelet for a three-phase short circuit fault in the HVDC transmission line.

It can be concluded from the bar graphs of the voltage signal, as shown in figure XII; (a), (b), and (c), that the bior5.5 is the most suitable mother wavelet for detecting a three-phase fault based on SD, variance and range parameters.

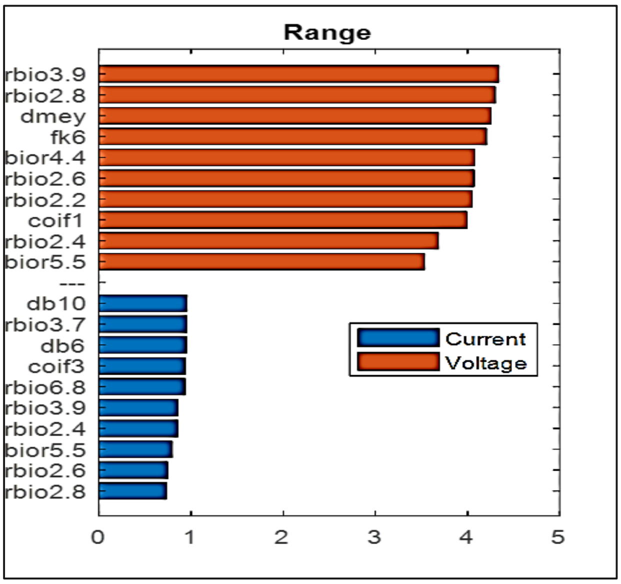
In contrast, by analyzing the current signals as shown in figure XII; (a), (b), and (c), it can be observed that rbio3.9 based on SD and variance however, based on range parameter rbio2.8 is the most suitable mother wavelet to detect a three-phase short circuit fault.



(a)



(b)



(c)

Figure XII: (a), (b), and (c); Comparison between Mother Wavelets for Three-Phase Short Circuit Fault

F. CASE VI: Three-Phase to Ground Fault

In this case, a three-phase to a ground fault has been applied on the HVDC transmission line. It can be seen from figure XIII that the DC line voltage (VdL) falls to -0.388 per unit at time 0.720s, while the current is increased to 1.928 per unit at 0.709s. As soon as the system detects a low voltage, the protection system is activated.

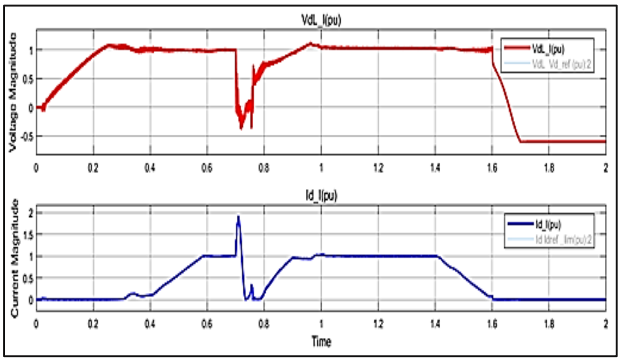
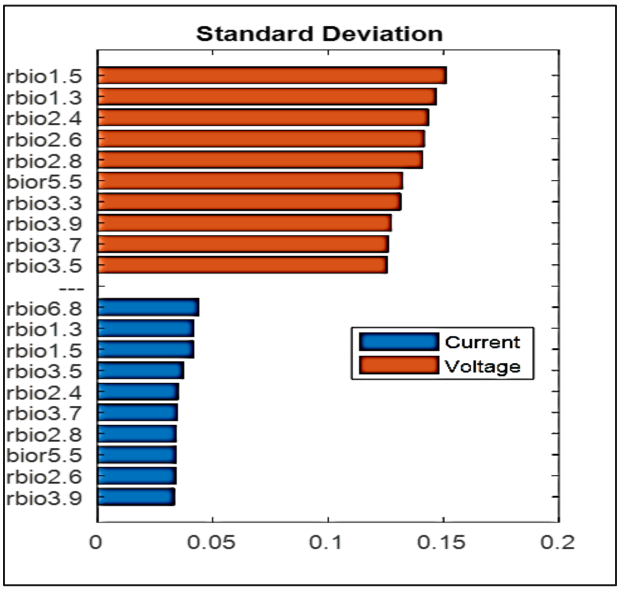
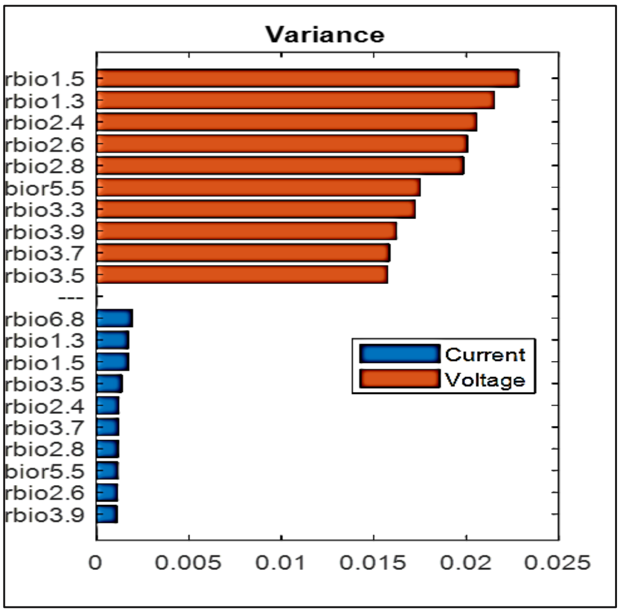


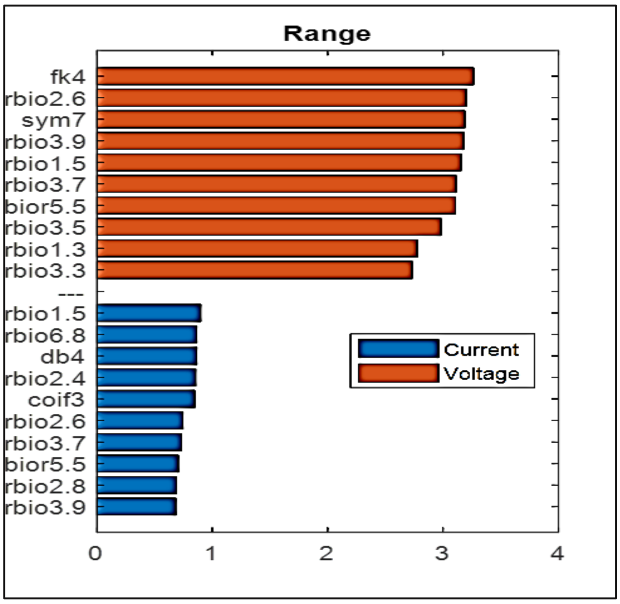
Figure XIII: Voltage and Current for Three Phase to Ground Fault



(a)



(b)



(c)

Figure XIV: (a), (b), and (c); Comparison between Mother Wavelets for Three Phase to Ground Fault

Figure XIV compares all mother wavelets to select the best mother wavelet for three-phase to ground. From the bar graphs of the voltage signals as shown in figure XIV; (a), (b), and (c), it is clear that based on SD and variance parameters rbio3.5 and based on range parameter, rbio3.3 is the most suitable mother wavelet to extract data from detailed coefficients at the 6th level of decomposition.

Table II: Summarized Result (Current Signal)

Current Signal			
Faults	**Standard Deviation**	**Variance**	**Range**
DC Cable	Rbio3.9	Rbio3.9	Db9
SLG	Rbio3.9	Rbio3.9	Rbio3.9
LLG	Bior5.5	Bior5.5	Rbio3.5
LL	Rbio3.9	Rbio3.9	Rbio1.3
LLL	Rbio3.9	Rbio3.9	Rbio2.8
LLLG	Rbio3.9	Rbio3.9	Rbio3.9

Table III: Summarized Result (Voltage Signal)

Voltage Signal			
Faults	**Standard Deviation**	**Variance**	**Range**
DC Cable	Db4	Db4	Coif4
SLG	Bior5.5	Bior5.5	Bior5.5
LLG	Bior5.5	Bior5.5	Rbio1.3
LL	Rbio3.5	Rbio3.5	Rbio3.9
LLL	Bior5.5	Bior5.5	Bior5.5
LLLG	Rbio3.5	Rbio3.5	Rbio3.3

However, rbio3.9 is considered the most suitable mother wavelet to detect three-phase to the ground by analyzing the current signal based on all three parameters.

The table II and table III above explains all we've learned from this effort so far.

Time-frequency techniques allow faster, easier, and more accurate methods to identify HVDC transmission line faults. This helps in developing innovative high-speed HVDC transmission line protection schemes. This research is intended to ensure the HVDC transmission system's security by investigating the fault detection technique based on time-frequency analysis. This is done by selecting a suitable algorithm with different mother wavelets in transient conditions to eliminate the various faults in the HVDC system.

V. CONCLUSION

This paper presents a method to determine an appropriate mother wavelet for various faults in the HVDC transmission line based on variance, standard deviation, and range parameters. This work proposes orthogonal and biorthogonal mother wavelets for multiple fault conditions on the HVDC transmission line. Orthogonal mother wavelets are considered better for analyzing signals. The variance, standard deviation, and range were formerly thought to provide the same MW, however, in a few fault instances, the range has proposed a different MW than the other two parameters. The simulation results reveal that mother wavelets can detect the occurrence of faults, although their behavior varies depending on the fault type. So to detect a specific fault, there is a need for a particular MW. In future work, ANN can be used to identify and categorize faults in the HVDC transmission line, and one or two mother wavelets can be chosen for all types of faults.

Acknowledgment

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

Authors Contributions

The contribution of the authors was as follows: Muhammad Tarique Chachar's contribution to this study was the concept, technical implementation, and correspondence. The methodology to conduct this research work was proposed by Aslam Pervez Memon along with

data collection and supervision. Jamshed Ahmed Ansari facilitated the data compilation, validation, project administration, and paper writing.

Conflict of Interest

The authors declare no conflict of interest and confirm that this work is original and not plagiarized from any other source, i.e., electronic or print media. 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.

References

[1] Shah, S. F. A., Sajjad, M. I. A., Khan, M. F. N., Farooq, H., & Rasool, A. (2019). Voltage Control and Power Loss Reduction in an Active Distribution Network using Solid State Transformers. *Sir Syed University Research Journal of Engineering & Technology, 9*(2).

[2] Keshri, J. P., & Tiwari, H. (2020). Fault Location Methods in HVDC Transmission System—A Review. *Intelligent Computing Techniques for Smart Energy Systems*, 411-419.

[3] Ghoughari, R. S., Shahbazzadeh, M. J., & Eslami, M. (2020). DC ARC Fault Location In VSC-HVDC Systems Based on Deep Learning Using PMU.

[4] Shaikh, S. A., Shaikh, A. M., Shaikh, M. F., Jiskani, S. A., & Memon, Q. A. (2022). Technical and Economical Evaluation of Solar PV System for Domestic Load in Pakistan: An Overlook Contributor to High Tariff and Load Shedding. *Sir Syed University Research Journal of Engineering & Technology, 12*(1), 23-30.

[5] Mahajan, S., & Kulkarni, S. U. (2016). A review on protection techniques used in HVDC transmission line. *Int. J. Sci. Res. Sci., Eng. Technol, 2*(3), 5.

[6] Maheshwari, A., Agarwal, V., & Sharma, S. K. (2018). Transmission line fault classification using artificial neural network based fault classifier. *Int. J. Electr. Eng. Technol.(IJEET), 9*, 170-181.

[7] da Silva, D. M., Costa, F. B., Miranda, V., & Leite, H. (2019). Wavelet-based analysis and detection of traveling waves due to DC faults in LCC HVDC systems. *International Journal of Electrical Power & Energy Systems, 104*, 291-300.

[8] Naidu, O. D., & Pradhan, A. K. (2018). A traveling wave-based fault location method using unsynchronized current measurements. *IEEE Transactions on Power Delivery, 34*(2), 505-513.

[9] Ukil, A., Yeap, Y. M., & Satpathi, K. (2020). Time-frequency domain analysis: wavelet-transform based fault detection. *In Fault Analysis and Protection System Design for DC Grids* (pp. 223-242). Springer, Singapore.

[10] Yeap, Y. M., & Ukil, A. (2014, October). Wavelet based fault analysis in HVDC system. In *IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society* (pp. 2472-2478). IEEE.

[11] Keswani, R. A. (2008, July). Identification of fault in HVDC converters using wavelet based multi-resolution analysis. In *2008 first international conference on emerging trends in engineering and technology* (pp. 954-959). IEEE.

[12] Li, Z. (2019). *Wavelet Transform Based Methods for Fault Detection and Diagnosis of HVDC Transmission Systems* (Doctoral dissertation, The University of Wisconsin-Milwaukee).

[13] Li, Z. Q., & Lv, Y. P. (2008, November). A novel scheme of HVDC transmission line voltage traveling wave protection based on wavelet transform. In *2008 International Conference on High Voltage Engineering and Application* (pp. 163-167). IEEE.

[14] Rajesh, K., & Yadaiah, N. (2005, August). Fault identification using wavelet transform. In *2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific* (pp. 1-6). IEEE.

[15] Venkatesh, C., & Rao, P. V. (2016, March). Wavelet-ANN based classification of HVDC converter faults. In *2016 IEEE 6th International Conference on Power Systems* (ICPS) (pp. 1-5). IEEE.

[16] Thwe, E. P., & Oo, M. M. (2016). Fault detection and classification for transmission line protection system using artificial neural network. *Journal of Electrical and Electronic Engineering, 4*(5), 89-96.

[17] Johnson, J. M., & Yadav, A. (2016). Fault location estimation in HVDC transmission line using ANN. In *Proceedings of First International Conference on Information and Communication Technology for Intelligent Systems: Volume 1* (pp. 205-211). Springer, Cham.

[18] Sun, X., Tong, X., & Yin, J. (2012, March). Fault diagnosis for VSC-HVDC using wavelet transform. In *2012 Asia-Pacific Power and Energy Engineering Conference* (pp. 1-4). IEEE.

[19] Zhou, Z., Jin, Q., & Zhang, Y. (2015, September). Discrete wavelet transform based fault analysis and identification in flexible HVDC transmission system. In *2015 International Forum on Energy, Environment Science and Materials* (pp. 799-803). Atlantis Press.

[20] Xie, J. W., Bi, G. H., Chen, S. L., & Zhang, J. (2014). An earth fault section identification method based on ANN. In *Advanced Materials Research* (Vol. 1006, pp. 913-918). Trans Tech Publications Ltd.

[21] Li, D., Song, G., Gao, S., Jin, X., & Suonan, J. (2013). Study on automatic fault location for VSC-HVDC transmission lines based on one-terminal traveling wave. *Power System Technology, 37*, 1128-1133.

[22] Troitzsch, C., Marten, A. K., & Westermann, D. (2016). Non-telecommunication based DC line fault detection methodology for meshed HVDC grids. *IET Generation, Transmission & Distribution, 10*(16), 4231-4239.

[23] Mitra, B., Chowdhury, B., & Manjrekar, M. (2016, September). Fault analysis and hybrid protection scheme for multi-terminal HVDC using Wavelet transform. In *2016 North American Power Symposium* (NAPS) (pp. 1-6). IEEE.

[24] Wu, J., Li, H., Wang, G., & Liang, Y. (2016). An improved traveling-wave protection scheme for LCC-HVDC transmission lines. *IEEE Transactions on Power Delivery, 32*(1), 106-116.

[25] Murthy, P. K., Amarnath, J., Kamakshiah, S., & Singh, B. P. (2008, December). Wavelet transform approach for detection and location of faults in HVDC system. In *2008 IEEE Region 10 and the Third international Conference on Industrial and Information Systems* (pp. 1-6). IEEE.

[26] Yeap, Y. M., & Ukil, A. (2014, October). Wavelet based fault analysis in HVDC system. In *IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society* (pp. 2472-2478). IEEE.

[27] Ahmed, N., Ram, N., Memon, A. P., & Ahmed, S. (2020, January). Comparative analysis of fault detection for HVDC transmission system using wavelet transform based on standard deviation. In *2020 3rd International Conference on Computing, Mathematics and Engineering Technologies* (iCoMET) (pp. 1-6). IEEE.

[28] Yeap, Y. M., Geddada, N., Satpathi, K., & Ukil, A. (2018). Time- and frequency-domain fault detection in a VSC-interfaced experimental DC test system. *IEEE Transactions on Industrial Informatics, 14(*10), 4353-4364.

[29] Fathabadi, H. (2015). Two novel proposed discrete wavelet transform and filter based approaches for short-circuit faults detection in power transmission lines. *Applied Soft Computing, 36*, 375-382.

[30] Montoya, R., Poudel, B. P., Bidram, A., & Reno, M. J. (2022). DC microgrid fault detection using multiresolution analysis of traveling waves. *International Journal of Electrical Power & Energy Systems, 135*, 107590.

[31] Jnaneswar, K., Mallikarjuna, B., Devaraj, S., Roy, D. S., Reddy, M., & Mohanta, D. K. (2021). A real-time DWT and traveling waves-based multi-functional scheme for transmission line protection reinforcement. *Electrical Engineering, 103*(2), 965-981.

[32] Muniappan, M. (2021). A comprehensive review of DC fault protection methods in HVDC transmission systems. *Protection and Control of Modern Power Systems, 6*(1), 1-20.

[33] Wu, H., Wang, Q., Yu, K., Hu, X., & Ran, M. (2020). A novel intelligent fault identification method based on random forests for HVDC transmission lines. *Plos one, 15*(3), e0230717.

[34] Ankar, S. J., & Yadav, A. (2021). A high-speed protection strategy for bipolar CSC-Based HVDC transmission system. *Electric Power Components and Systems, 49*(1-2), 48-66.

[35] Mukherjee, A., Kundu, P. K., & Das, A. (2021). Transmission line faults in power system and the different algorithms for identification, classification and localization: a brief review of methods. *Journal of The Institution of Engineers (India): Series B, 102*(4), 855-877.

[36] Joshi, A., Khathoon, R., Peter, P. A., & Vinod, V. (2022, January). A computationally less expensive fault detection technique in VSC-HVDC system using wavelet decomposition and support vector machine classifier. In *2022 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE)* (pp. 1-6). IEEE.

[37] Li, M. (2022). DC Microgrid Protection. (PhD Doctorate, University of New South Wales). Retrieved from; http://hdl.handle.net/1959.4/100466

[38] Rizwan, M., Waseem, M., Liaqat, R., Sajjad, I. A., Dampage, U., Salmen, S. H., ... & Annuk, A. (2021). SPSO Based Optimal Integration of DGs in Local Distribution Systems under Extreme Load Growth for Smart Cities. *Electronics, 10*(20), 2542.

[39] Aziz, T., Lin, Z., Waseem, M., & Liu, S. (2021). Review on optimization methodologies in transmission network reconfiguration of power systems for grid resilience. *International Transactions on Electrical Energy Systems, 31*(3), e12704.

[40] Ünal, F., & Ekici, S. (2017, April). A fault location technique for HVDC transmission lines using extreme learning machines. In *2017 5th International Istanbul Smart Grid and Cities Congress and Fair (ICSG)* (pp. 125-129). IEEE.

[41] Wang, X., Xu, J., & Zhao, Y. (2018). Wavelet based denoising for the estimation of the state of charge for lithium-ion batteries. *Energies, 11*(5), 1144.

[42] Zhang, X., Mi, C. C., Masrur, A., & Daniszewski, D. (2008). Wavelet-transform-based power management of hybrid vehicles with multiple on-board energy sources including fuel cell, battery and ultracapacitor. *Journal of Power Sources, 185*(2), 1533-1543.