Fault Location in Extra Long HVdc Transmission Lines using Continuous Wavelet Transform

Kasun Nanayakkara, A.D. Rajapakse, Randy Wachal

***Abstract*-- In this paper, fault location accuracies in a 2400 km long overhead HVdc line and 300km long underground cable HVdc line using the two-terminal travelling wave method are investigated. The paper proposes to use continuous wavelet transform for detecting the arrival time of travelling waves, and shows that it provides better accuracy when compared with the commonly used discrete wavelet transform based technique. Furthermore, the results show that the continuous wavelet transform based wave front detection can provide adequate accuracy in the fault location in extra long overhead lines and long underground cables. The influence of noise on the fault location accuracy is discussed. The results also show that either dc terminal voltages or the surge capacitor currents can be used in dc line fault location.**

***Keywords*: HVdc, continuous wavelet transform, dc line fault location, transmission lines, cables, travelling waves**

I. INTRODUCTION

WITH the rapid development of HVdc technology, HVdc transmission systems with extra long overhead (OH) lines such as the 2500 km long Porto Velho-São Paulo HVdc system [1] and HVdc systems with extra long underground (UG) cables such as the 295km long Basslink HVdc system [2] are under consideration. Accurate fault location in such extra long dc lines is a challenging task.

Fault location in extra long HVdc systems is currently achieved with the help of repeater stations [3]. Installation of extra hardware at the repeater stations, which are required to locate line faults using the existing technology, increases the cost of these transmission projects. This paper investigates whether the faults can be located accurately only using the terminal measurements, thereby eliminating the cost of extra hardware required in the repeater stations.

Travelling-wave-based line fault location principle [4] has been successfully applied to transmission line fault location in the conventional HVdc systems with two terminals. The key requirement to improve the accuracy of fault location long lines is precise detection of wave front arrival times. In most of the recently published research [5]-[8], surge arrival times have been detected using discrete-wavelet transform (DWT) coefficients of the measured signal. Wavelet transform works well for analyzing transient in signals because of its simultaneous time and frequency localization capabilities. Availability of software tools and lower computational burden have made discrete version of the wavelet transform, DWT, is the common choice for implementation of these improved fault location algorithms.

Compared to the DWT, the continuous-wavelet transform (CWT) provides more detailed and continuous analysis of a fault transient [9]. In CWT, the analyzing wavelet is shifted smoothly along the time axis of the input signal. Therefore, CWT coefficients have better time resolution which is very important to have high accuracy in travelling wave based dc line fault location. Hence, as shown in this paper, the CWT approach allows obtaining fault location accuracy better than that obtained with the DWT coefficients.

All studies were carried out with detailed models of HVdc converters and transmission lines simulated in PSCAD/EMTDC and the fault location algorithm was implemented in MATLAB. The appropriate type and scale of continuous wavelet transform coefficients at a given sampling rate was found through the simulation studies. The importance of calibrating the travelling wave speed, which is depended on the scale of the wavelet coefficients used, is highlighted. Furthermore, the accuracy of the fault location of the proposed method was studied under noisy input signals.

II. TRAVELLING WAVE BASED DC LINE FAULT LOCATION

Travel times of the fault initiated surges are used to find the dc line fault location in the travelling wave based fault location method. Fig. 1 shows the flow of the travelling waves along a dc line with length L. Assume that these waves are initiated due to a fault located at distance x_F away from terminal-T_1 and the waves travel at a constant velocity denoted by v.

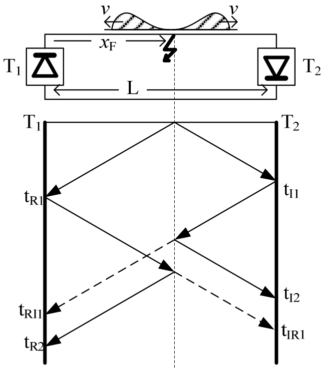

Fig. 1 - Lattice diagram to illustrate the travelling wave flow along the dc line

Dc line fault location can be calculated as shown in (1) using the travelling wave arrival time with respect to a single terminal (T_1). This method is called a single-ended method or

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Type A method [10].

$$x_F = \frac{(t_{R2} - t_{R1}) \times v}{2} \tag{1}$$

Fault location can also be found as shown in (2) using the initial travelling wave arrival time at both the terminals. This method is called double-ended method or *Type D* method [10].

$$x_F = \frac{(L - (t_{I1} - t_{R1}) \times v)}{2} \tag{2}$$

In the single-ended method the analysis of the waveforms has to be more sophisticated [10]. As an example consider the case shown in Fig. 1, where the fault location x_F is greater than *L/2*. The reflected wave from the T_2 terminal arrives before (Wave arrival time: t_{RI1}) the second reflection (Wave arrival time: t_{R2}). Therefore, signature analysis may be required to distinguish the two waveforms [10]. The double-ended method is based on timings from the initial surges and hence the reflected waves are not involved. However double-ended method requires both an accurate method of time synchronization and an easy means of brining the measurements from the two terminals to a common point.

GPS provides time synchronization accuracies of 1µs [10]. The fault location calculation does not have to be 'on-line' [10] and typically HVdc systems have communication channels installed for control purposes and these channels can be used to send the necessary time information for the dc line fault location. Therefore two-terminal method which is used in this paper is more reliable and preferred over the single-ended method.

III. IDENTIFICATION OF THE SURGE ARRIVAL TIME

Precise identification of the surge arrival time is very important to have high accuracy in the travelling wave based line fault location method. Conventional edge detection methods such as Short-Time Fourier Transform (STFT) and Finite Impulse Response (FIR) filtering based methods [6], [10] will not provide adequate accuracy in identifying the travelling wave arrival time. Wavelet transform can be used to identify the wave-front arrival time because of its simultaneous time and frequency localization capabilities [9]. Recently man researches have put their efforts to use wavelet transform in HVdc fault location such as [5], [6], [7] [8] and [11].

A. Wavelet transform to identify the surge arrival time

Wavelet transform is a linear transformation similar to the Fourier transform [12]. However, it is different from Fourier transform because it allows time localization of different frequency components of a given signal [12]. In the case of the wavelet transform, the analyzing functions are called mother wavelets and are defined as (3),

$$\varphi_{p,\tau}(t) = \frac{1}{\sqrt{p}} \varphi^{*}\left(\frac{t-\tau}{p}\right) \tag{3}$$

A given mother wavelet (φ) has a location or time shift (τ) and a scale or duration (p). In the wavelet transform these shift and scale values are adjusted. This is called multi resolution analysis and it is useful for analyzing fault transients [10].

In this study, fault location accuracy was tested using family of Daubenchie (*db*) mother wavelet types and according to the results '*haar*' mother-wavelet (also called *db2* mother wavelet), was found to be the most suitable. Shape of the '*haar*' mother-wavelet is shown in Fig. 2 and it is considered the simplest mother wavelet type available. Therefore, it is expected to be computationally less demanding and requires less resources when implementing in hardware.

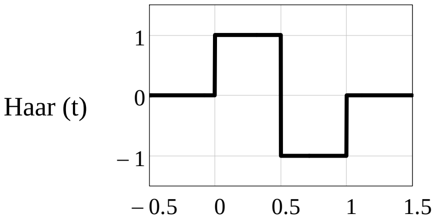


Fig. 2 - The Haar mother wavelet

B. Discrete Wavelet Transform (DWT) and Continuous Wavelet Transform (CWT) based dc line fault location

In the DWT, the signal is broken in to dyadic blocks or the shifting and the scaling is based on a power of 2. The CWT still uses discretely sampled data, however the shifting process is a smooth operation across the length of the sampled data, and the scaling can be defined from the minimum (original signal scale) to a maximum chosen value. Therefore CWT provides finer resolution. The trade off for this improved resolution is an increased computational time and memory required to calculate the wavelet coefficients. The trade off can be compensated for the accuracy since the dc line fault locator performs off-line calculations.

Comparison of the DWT and CWT coefficient magnitude values of the rectifier terminal voltage measurement in an HVdc system with 2400km long OH line is shown in Fig. 3. In this case, a line to ground fault occurred 625 km from the rectifier end at 2.4 s time.

Fig. 3(a) shows the rectifier end terminal voltage monitored from the simulations. Terminal voltage is sampled at 2MHz sampling frequency and normalized between 0-20 V. CWT of the signal is calculated for 4, 8, 16 and 32 scale values and the magnitude of these coefficients are shown in Fig. 3(b), (c), (d) and (e) respectively. If a proper threshold value is set then the initial surge arrival point can be easily detected by using the scale values. Further, DWT of the signal is calculated for levels 2, 3, 4 and 5 which are equivalent to selected CWT scale values in frequency bands. Magnitudes of detail coefficients of DWT are also shown in Fig. 3(b), (c), (d) and (e) respectively. It can be clearly visible that the corresponding DWT values are poor in time resolution and also are smaller in magnitude compared with CWT coefficients. That is the main reason why the CWT based fault location method gives better accuracy than DWT based fault location method.

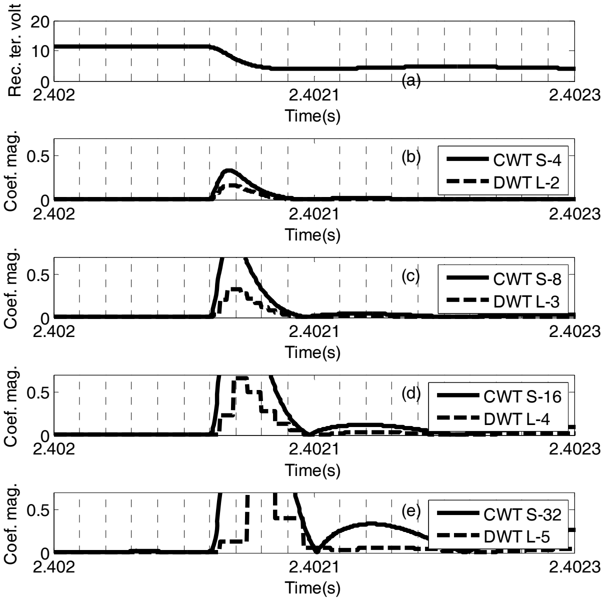


Fig. 3 - Rectifier end terminal voltage DWT and CWT coefficient magnitude values when a line to ground fault occurred (625 km away from the rectifier end applied at 2.4s)

IV. DC LINE FAULT LOCATION METHOD

The proposed simplified fault location algorithm which is an offline calculation is illustrated in Fig. 4. This calculation can be initiated once the primary protection scheme identifies the dc line fault. The fault location scheme maintains a runtime input data buffer, which will be saved when a fault is detected. The size of this buffer depends on factors such as the primary protection time delay, sampling time and the transmission line length of the specific HVdc scheme.

The largest time delay in the system is used to estimate the buffer size. For example, consider that the primary protection scheme has 1 ms time delay and the data acquisition rate is 2MHz for a HVdc scheme with a transmission line length of 2400km. The worst case travel time of the surge is approximately equal to 8ms (assuming $3*10^5$ km/s propagation velocity) when the fault is closer to one end of the line. In this case, the primary protection time delay (1ms) is smaller than the worst case travelling wave time delay. Therefore the buffer size is determined by the travel time and the required value is 16000 samples at 2 MHz. With a safety margin the buffer size can be taken as double of this value (32000 samples). Data acquisition boards with sufficient on board memory meet such requirements are commercially available.

In this research, both terminal voltage and surge capacitor current measurements were tested as potential input signals. Sampling is assumed synchronized and time tagged using GPS clock signals. Wavelet transform either DWT or CWT is applied to the input signal and the magnitude values of the wavelet coefficients are extracted.

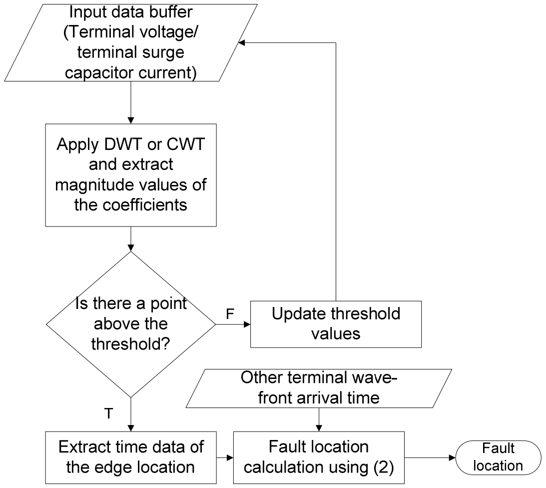


Fig. 4 - Simplified fault location algorithm

A threshold to identify the surge arrival point is set about 15% above the maximum value of the wavelet coefficient of the corresponding input signal under the normal conditions. The safety margins are required to allow for the noise. Different threshold values are found for each coefficient scale considered in the algorithm.

The time when the magnitude of the considered coefficient rises above the threshold is recognized as the time of arrival of a surge at the terminal. From the measurements at the other end of the transmission line, the time of arrival of the surge in that terminal is received via telecommunication channel. Fault location is calculated by using the travelling wave principle according to (2).

As different coefficient scales or levels represent different frequency bands in the signal, the velocity of propagation at each of these frequency bands could slightly differ. These velocities can be found and the algorithm can be calibrated by using test data for a known fault.

The algorithm attempts to find an arrival of surge in the current data buffer, and if it did not find an edge, then the buffer window is shifted and the procedure is repeated.

Note that if the signal processing can be done in real time, the occurrence of a fault can be detected by continuously observing the wavelet coefficients, without depending on an external initiation signal. With fast digital signal processors (DSPs), this is also a practically viable approach.

V. SIMULATION MODELS

Simulations were done using two HVdc transmission networks, one with OH transmission line and the other with UG cable line. All the test networks are based on the modified version of the first Cigré benchmark HVdc scheme [13]. This test network has 500kV as the nominal dc voltage and it is designed to deliver 1000MW of active power. Furthermore, a bipolar HVDC configuration is used since most of the present day HVDC systems are built in bipolar configuration, instead of the mono-polar arrangement in the original reference [13].

The simplified PI model representing a cable dc line scheme in the original Cigré model [13] was replaced with a frequency dependent distributed parameter model of a 2400km long overhead transmission line in one of the test network and in the other test network, it was replaced with a frequency dependent distributed parameter model of a 300 km long underground cable line. Schematic diagram of the test networks are shown in Fig. 5.

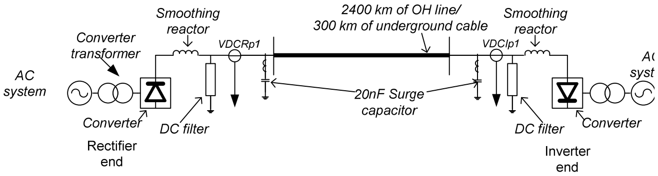
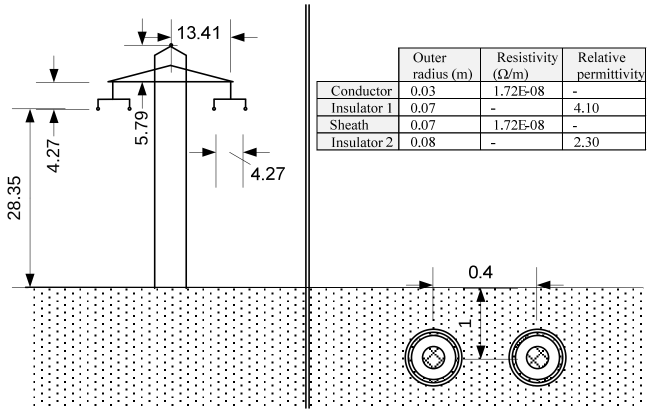


Fig. 5 - HVdc test networks modeled in PSCAD/EMTDC

The original test network does not contain a surge capacitor. Surge capacitor is used to protect converter station equipment from surges travelling alone the dc line. When a steep wave-front of surge travelling along the dc transmission line is first slowed down by the line surge impedance and then by the surge capacitor. Since the use of surge capacitor current to detect surge arrival as in the existing fault locator installed at the Nelson River HVDC scheme [14] to be investigated, a 20 nF surge capacitor is added to the test networks.

A series dc reactor is important in line commutated type HVdc system [15]. However, original test network does not contain a separate smoothing reactor because it is included in the simplified cable model. Typical value of the smoothing reactor is in the range of 0.5-1H [15]. Therefore, 0.5H smoothing reactor is placed in series with the transmission line at both ends.

Tower structure for the OH dc line and Cable parameters for the UG dc line are shown in Fig. 6. All the distance measurements are shown in meters. The test networks are modeled in PSCAD/EMTDC. The terminal voltage and surge capacitor current measurements are monitored for large number of simulation cases with different dc line fault locations. The input signals were conditioned assuming 2 MHz sampling rate, 16-bit Analog to Digital (A/D) conversion resolution, and 0-20 V range before use in the dc line fault location algorithm to understand the performance under presence of an A/D converter. These A/D parameters are selected after careful testing and considering the availability of commercial A/D converters.



	Outer radius (m)	Resistivity (Ω/m)	Relative permittivity
Conductor	0.03	1.72E-08	-
Insulator 1	0.07	-	4.10
Sheath	0.07	1.72E-08	-
Insulator 2	0.08	-	2.30

Fig. 6 - HVdc dc line parameters (Left: OH line tower structure and Right: UG cable parameters)

VI. SIMULATION RESULTS

The results of the dc line fault location method are presented for the two different test networks, HVdc system with 2400 km long OH dc line and HVdc system with 300 km long UG cable dc line. The tests were investigated the potential usage terminal voltage measurements and surge capacitor current measurements as the input signals to the algorithm. The results also compare the DWT based method and the CWT based method.

The results are presented using the absolute prediction error value obtained for different fault locations on the dc line. This value shows the magnitude difference between the predicted fault location and the actual fault location in kilometers.

A. HVdc test network with 2400 km long OH dc line

Fig. 7 shows the variations of the prediction error with the tested fault locations using CWT of the terminal voltage measurements to identify the travelling wave arrival time. The results are within ±350m prediction error using the scales up to 32. In general the lower scales give better accuracy.

Fig. 8 shows the prediction errors when the surge capacitor currents are used as the input signals. Overall accuracy is similar to the accuracy obtained with the terminal voltages as inputs. The results are within ±400m prediction error using the scales up to 32. In general the lower scales give better accuracy. These results indicate that surge capacitor current and terminal voltage measurements can be used as inputs in the dc line fault location algorithm.

Fig. 9 and Fig. 10 summarize the prediction error values obtained with DWT based method. In Fig. 9 the terminal voltages are used as the inputs for the fault location algorithm. According to the tested cases the prediction error is ±2.5km when detail coefficients up to level 5 are used. However less prediction error is visible in the lower levels.

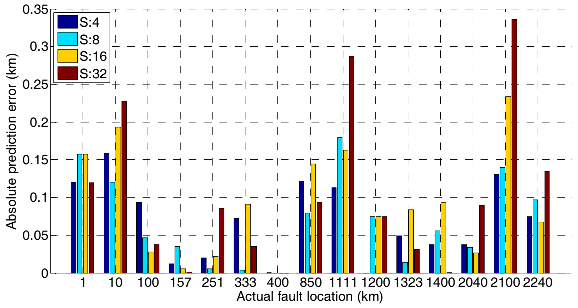


Fig. 7 - Fault location error based on CWT and using terminal voltage as input

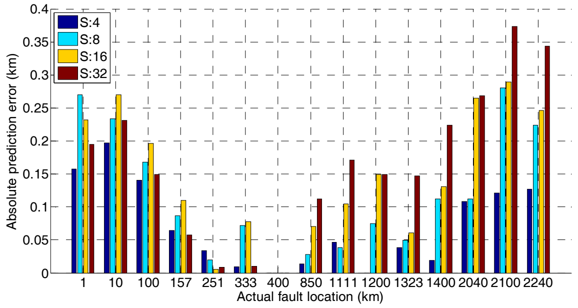


Fig. 8 - Fault location error based on CWT and using surge capacitor current as input

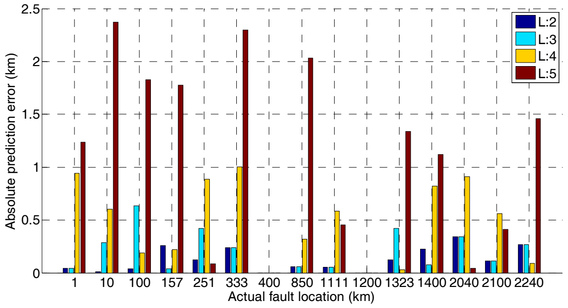


Fig. 9 - Fault location error based on DWT and using terminal voltages as inputs

In Fig. 10, detail coefficients of surge capacitor currents are used as inputs. The values indicate the prediction accuracy less than ±2.2km is achievable for the tested cases using levels up to 5. However better accuracy can be achieved with lower detail levels. It can be seen from the results for the test network with 2400 km of OH line that CWT based method provides better overall accuracy than the DWT based method.

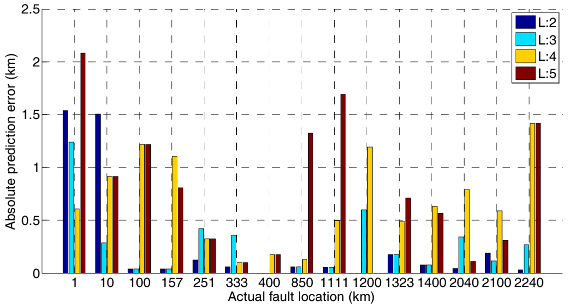


Fig. 10 - Fault location error based on DWT and using surge capacitor currents as inputs

B. *HVdc test network with 300 km long UG cable dc line*

Similar study was done with the 300 km long UG cable HVdc system. Fig. 11 and Fig. 12 show the prediction errors obtained with CWT method. In Fig. 11 terminal voltages are used as inputs. The prediction accuracy is ±200m for the test cases using scales up to 32.

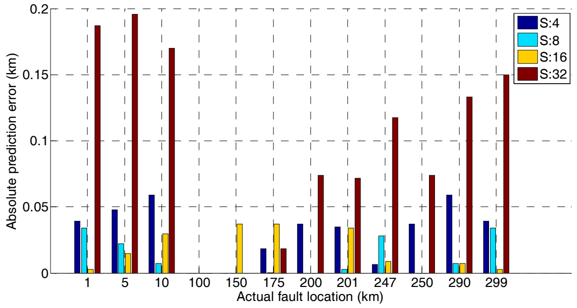


Fig. 11 - Fault location error based on CWT and using terminal voltage as input

Prediction error values found using surge capacitor currents as inputs are listed in Fig. 12. Maximum prediction error value of ±200m was observed using the scale 4. The results lie between the same margins obtained using terminal voltage measurement as inputs. Therefore the surge capacitor current can also be used as a potential input to this fault location algorithm even in case of UG cable HVdc system.

Fig. 13 and Fig. 14 show the results acquired using DWT of the terminal voltage measurements and the surge capacitor current measurements respectively. The results lay between ±1.8km in case of terminal voltages and ±3.5km in case of surge capacitor currents. Therefore it is clear that the CWT method provides better overall accuracy than the DWT method. Furthermore, the results also indicate that the same algorithm can be used in HVdc systems with UG cables.

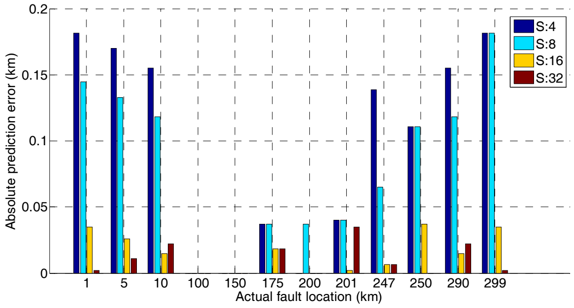


Fig. 12 - Fault location error based on CWT and using surge capacitor current as input

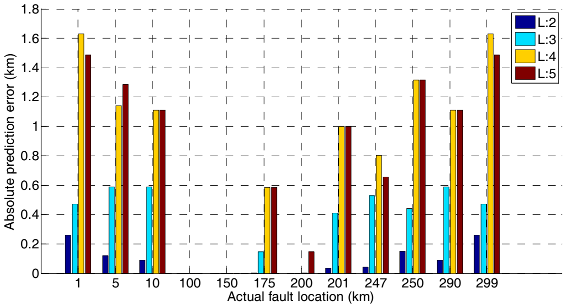


Fig. 13 - Fault location error based on DWT and using terminal voltages as inputs

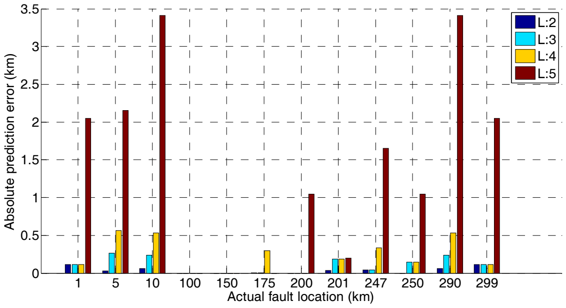


Fig. 14 - Fault location error based on DWT and using surge capacitor currents as inputs

C. *Effect of the noise in the input signal*

Performance of the fault location algorithm was tested with input signals contaminated with uniformly distributed random noise. This study was done for both test networks. As an example, Fig. 15 shows rectifier terminal voltage and surge capacitor current contaminated with noise in the HVdc system with OH dc line. In Fig. 15 (a), rectifier end voltage with added 0.001 pu white noise is compared with the clean signal. In Fig. 15 (b), the same signal with 0.01 pu white noise is shown.

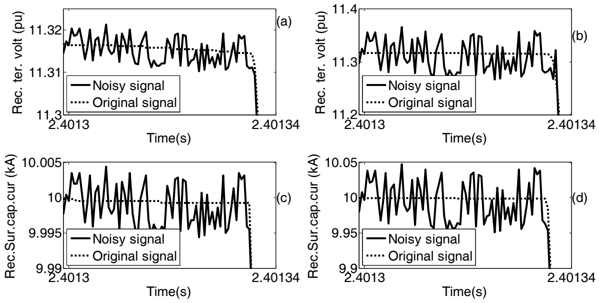


Fig. 15 - Surge capacitor current and terminal voltage with added noise

Fig. 15 (c) and (d) compare the rectifier end surge capacitor current with 0.001 kA and 0.01 kA noise respectively with the clean signal. In the following sections results obtained with CWT based method are presented for the two test networks.

1) HVdc test network with 2400 km long OH dc line

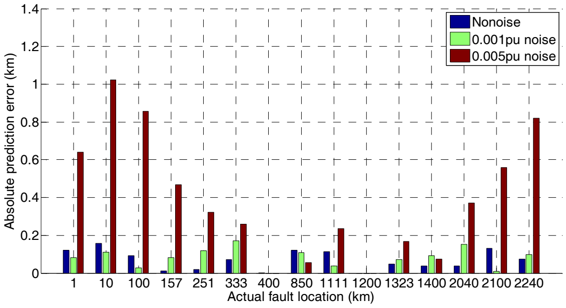


Fig. 16 - Prediction errors for different noise levels in the terminal voltages (Using CWT Scale 4)

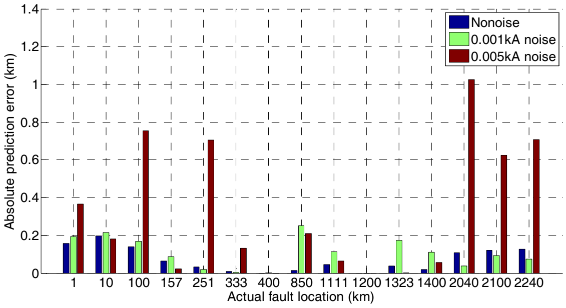


Fig. 17 - Prediction errors for different noise levels in the surge capacitor current measurements (Using CWT Scale 4)

Fig. 16 compares the prediction error results obtained with terminal voltage measurements contaminated with 0.005 pu noise, 0.001pu noise and normal no noise condition. Fig. 17 compares the prediction error results obtained with surge capacitor current measurements contaminated with 0.005 kA noise, 0.001kA noise and normal no noise condition.

In both of these cases only CWT scale 4 coefficients are used which is usually given the lowest errors. According to the result with increasing noise level the performance of the fault location is reduced.

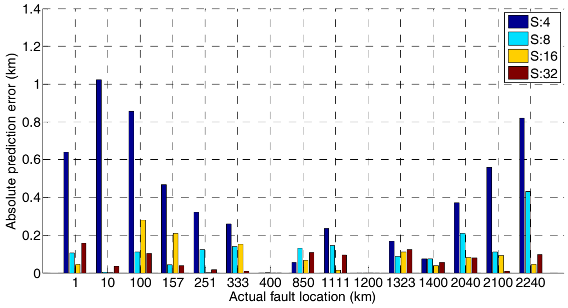


Fig. 18 - Comparison of prediction errors using different CWT scales for terminal voltage with 0.005pu of noise

As can be seen in Fig. 18, it was found that lower scales are more sensitive to noise than the higher scales. Therefore when the noise is present in the input signals, use of higher scales (Scales 16 and 32) CWT coefficients may be desirable to achieve robust results.

2) HVdc test network with 300 km long UG cable dc line

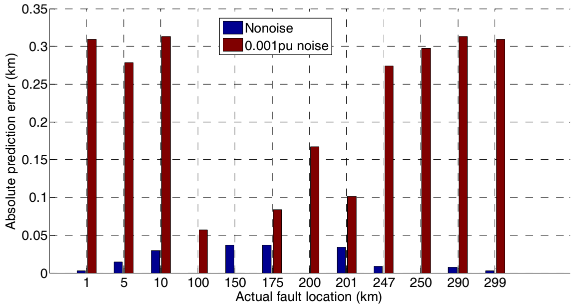


Fig. 19 - Prediction errors for different noise levels in the terminal voltages (Using CWT Scale 16)

The results obtained for the UG cable test network are presented in Fig. 19 and Fig. 20. It was found that cable based test network is more sensitive to noise and therefore higher scales (Scale 16) is used to present the results. Fig. 19 compares the prediction errors using terminal voltage measurements contaminated with 0.001pu noise and no noise. Fig. 20 compares the prediction errors using surge capacitor measurements contaminated with 0.001kA noise and no noise.

It is clearly visible that the performance of the fault location algorithm is sensitive to the noise in the input signal. As can be seen in Fig. 21, it was found that lower scales are more sensitive to noise than the higher scales. Therefore when the noise is present in the input signals, use of higher scales (Scales 16 and 32) CWT coefficients may be desirable to achieve robust results.

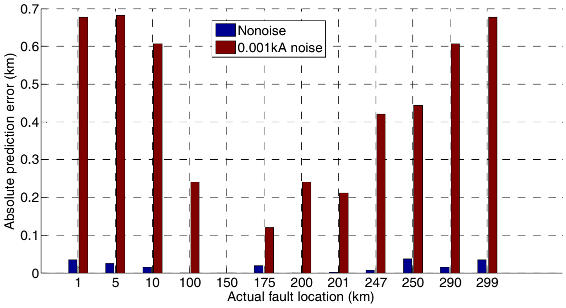


Fig. 20 - Prediction errors for different noise levels in the surge capacitor current measurements (Using CWT Scale 16)

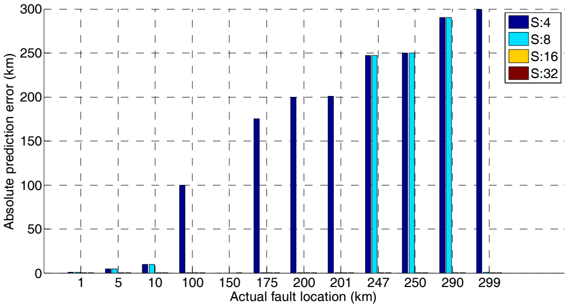


Fig. 21 - Comparison of prediction errors using different CWT scales for terminal voltage with 0.001pu of noise

VII. CONCLUSIONS

An algorithm to locate faults on an extra long HVdc line using the terminal measurements was proposed. The proposed algorithm that uses two-terminal travelling wave fault location principle has the ability to correctly identify dc line fault location in both HVdc systems with OH line and UG cables. The analysis considered the scaling and quantization effects of the A/D conversion and indicated that either of the terminal voltage or the surge capacitor current can be used as the input signal, with 2 MHz sampling rate, 16-bit resolution and 0-20V range.

Wavelet transform is used to accurately detect the arrival time of travelling waves at the converter terminals. It was shown that the scheme which uses continuous wavelet transform coefficients yields more robust and accurate wave front detection compared to the scheme that uses discrete wavelet transform coefficients.

Application of the proposed fault location method to HVdc systems consisting of 2400 km long overhead line and 300 km long underground cable line were demonstrated through simulations. The simulation results verified the correct operation of the fault location algorithm. According to the simulation results, it is possible to achieve fault location prediction error of ±400m for the test system with 2400 km OH line using either terminal voltage or surge capacitor current measurements as inputs. The simulation results also show this algorithm works with 300 km UG cable line and both inputs signals would produce similar accuracy levels: in the prediction error range of ±200m under normal conditions for permanent line to ground faults.

Simulations showed that the proposed method's accuracy degrade with the presence of measurement noise. It was found that the UG cable test network is more sensitive to noise than the OH line test network. However when the noise is present in the input signals, use of higher scales (Scales 16 and 32) CWT coefficients may be desirable to achieve robust results in both test networks.

VIII. REFERENCES

[1] B. Backwel. (2009, July). “ABB wins contract for world's longest HVDC link”, [Online].Available: http://www.rechargenews.com/energy/wave_tidal_hydro/article184870.ece

[2] T. Westerweller and J. Price, “Crossing the divide [Basslink HVDC interconnector],” *Power Engineer*, vol. 20, Oct. 2006, pp. 42-45.

[3] P. Chen, B. Xu, and J. Li, “A Traveling Wave Based Fault Locating System for HVDC Transmission Lines,” *International Conference on Power System Technology, 2006. PowerCon 2006*, 2006, pp. 1–4.

[4] EEE Std C37.114-2004, “IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines”, 2005.

[5] R.A. Keswani, “Identification of Fault in HVDC Converters Using Wavelet Based Multi-Resolution Analysis,” *2008 First International Conference on Emerging Trends in Engineering and Technology*, Nagpur, Maharashtra, India, 2008, pp. 954-959.

[6] P. Murthy, J. Amarnath, S. Kamakshiah, and B. Singh, “Wavelet Transform Approach for Detection and Location of Faults in HVDC System,” *Industrial and Information Systems conference,* 2008, pp. 1-6.

[7] J. Suonan, G. Shuping, S. Guobing, J. Zaibin, and K. Xiaoning, “A Novel Fault-Location Method for HVDC Transmission Lines,” *IEEE transactions on power delivery*, vol. 25, 2010, pp. 1203–1209.

[8] O.M.K.K. Nanayakkara, A.D. Rajapakse, and R. Wachal, “Fault Location in HVDC Transmission Lines Using Discrete Wavelet Transform”, presented at the 2010 Cigre Canada conf. on power systems, Vancouver, Canada, 2010.

[9] A. Borghetti, S. Corsi, C. Nucci, M. Paolone, L. Peretto, and R. Tinarelli, “On the use of continuous-wavelet transform for fault location in distribution power systems,” *International Journal of Electrical Power & Energy Systems*, vol. 28, Nov. 2006, pp. 608-617.

[10] M.M. Saha, J. Izykowski, and E. Rosolowski, *Fault Location on Power Networks*, Springer Verlag, 2009.

[11] L. Shang, G. Herold, J. Jaeger, R. Krebs, and A. Kumar, “Analysis and identification of HVDC system faults using wavelet modulus maxima,” *IEE conference publication*, 2001, pp. 315–320.

[12] F.H. Magnago and A. Abur, “Fault location using wavelets,” *Power Delivery, IEEE Transactions on*, vol. 13, 2002, pp. 1475–1480.

[13] M. Szechtman, T. Wess, and C.V. Thio, “A benchmark model for HVDC system studies,” *AC and DC Power Transmission, 1991., International Conference on*, 2002, pp. 374–378.

[14] T.W. Radford, “HVDC line fault locator upgrade”, in *Proc. HVDC operating conf.*, 1987, pp. 189-200.

[15] E.W. Kimbark, *Direct current transmission*, Wiley-Interscience, 1971.