

Improved travelling wave based fault location in VSC HVDC Cables using Rogowski coil measurements

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1 INTRODUCTION

Accurate location of the faults in HVDC transmission lines, which are employed to transport large amounts of power, is essential for taking corrective measures quickly and cost effectively. Travelling wave based fault location has been very successfully used for line fault location in line commutated converter (LCC) based HVDC schemes. Travelling wave based fault location systems give good accuracy, even for very long transmission lines [1]. However, there is little experience in application of these fault locaters in new voltage source converter (VSC) based HVDC systems. Many of the proposed VSC HVDC applications such as interconnection of offshore wind farms involve submarine or underground cables. Fault location in cables is more challenging than in overhead transmission lines, and at the same time demands higher accuracy of location. VSC HVDC schemes with long cables, over 300 km, have been proposed and therefore, it is very important to adapt the travelling waves based fault location technology for VSC HVDC systems and improve the accuracy to deal with extreme cases such as very long cables.

Although calculations involved in travelling wave based fault location schemes are simple in theory, their implementation is challenging due to various factors that contribute to errors. These include bandwidth limitations of transducers, A/D conversion and sampling precision, synchronization errors, wave front detection algorithm errors, propagation velocity deviations due to changes in physical parameters, and the propagation velocity variations in different frequency components of the travelling wave in lossy transmission lines. To increase the accuracy of the fault location scheme, improvement of every factor mentioned above is necessary. In this paper, we focus on the effect of propagation velocity variations in different frequency components of the travelling wave.

In a transmission line, high frequency components of a fault generated travelling wave travel at faster velocities than low frequency components. Fault generated transients contain a range of frequency components extending from low frequencies to several hundred kilohertz. High frequency components of the travelling wave, although travel faster, subjected to more attenuation as they travel along a cable, mainly due to the high dielectric losses [2]. Furthermore energy of the travelling wave is reduced due to $I^2 R$ losses along the cable. If a fault happen closer to one end, the travelling wave that propagate over a longer distance get attenuated, and it may not contain the highest frequency components when it reaches the other end. On the other hand, the travelling wave arriving at the closer

end would contain almost all frequencies. Errors occur when the travel time difference is estimated using two signals with different frequency contents. Although, this error is not significant in overhead lines and short cable, ignoring these errors due to uneven wave front attenuation leads to unacceptable errors in long cables.

This paper investigates the variation of the shape of the fault generated travelling wave and its effects on the speed of the travelling wave based fault location through simulations performed in PSCAD/EMTDC. The paper proposes a Rogowski coil based transient measurement system and simple filtering scheme to ensure that signals with the same frequency contents are considered for travel time difference estimation. Accuracy of the fault location calculation after the modification is confirmed through simulations.

2 TRAVELLING WAVE BASED 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. Figure 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 Converter-1 and the waves travel at a constant velocity denoted by u .

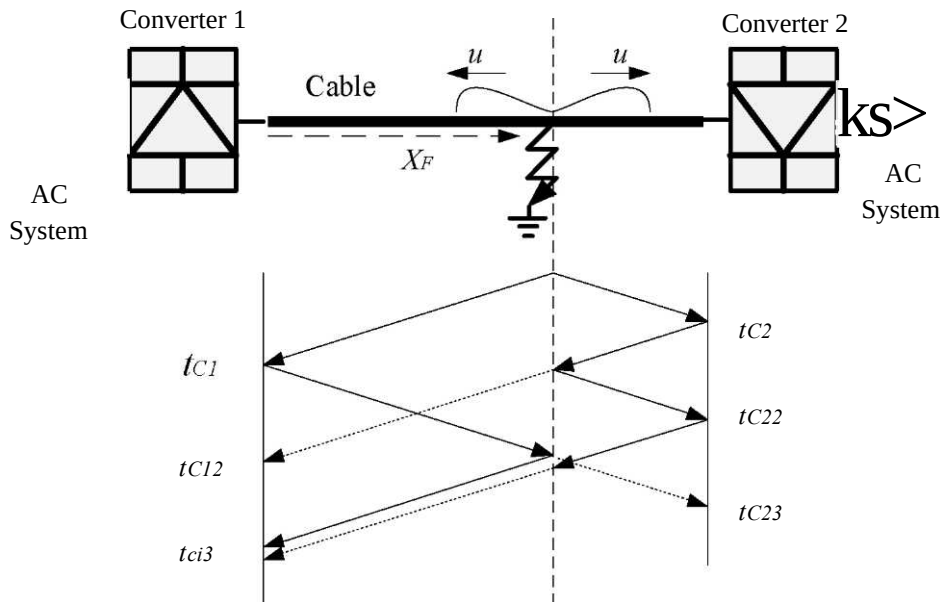


Figure 1: Lattice diagram to illustrate the travelling wave flow along the transmission

In this paper, only the double-ended method [3] of fault location is considered due to its reliability. Using the initial travelling wave arrival times at two terminals (t_{C1} and t_{C2} in Figure 1), the distance to the fault can be estimated as:

$$X_F = \frac{l - u \cdot (t_{C2} - t_{C1})}{2} \quad [1]$$

Since the double-ended method is based on timings from the initial surges, the reflected waves are not involved. In the single-ended method where reflected waves are used, the analysis of the waveforms has to be more sophisticated [4]. This is to discriminate between waves reflected from the fault and the remote terminal. However, double-ended method requires both an accurate method of time synchronization and an easy means of transmitting the measurements from the two terminals to a common point. GPS provides time synchronization accuracies of $1\mu s$ [4]. Since the fault location

calculation does not have to be 'real-time', data can be exchanged using the communication channels installed for HVDC converter control.

3 SIMULATION MODEL OF THE VSC HVDC SCHEME

The VSC HVDC scheme used for the simulation study is shown in Figure 2. Power rating of this VSC HVDC system is 200 MW and the pole to pole DC voltage is 400 kV. Both converters use pulse width modulation (PWM) control with a carrier frequency that is 33 times the fundamental frequency of the AC systems. Converter-1 controls AC voltage magnitude and DC voltage, while the Converter-2 controls the DC power and reactive power at the AC side. A 300 km long cable system connects the two converters. Cables were considered because it is more challenging to detect surge fronts in cables than overhead lines. The cables were modeled using frequency dependent phase domain model available in PSCAD/EMTDC software.

Detection of the fault generated surge arrival times can be achieved by measuring the current passing through the surge capacitor using a Rogowski coil sensor. This detection is possible due to the presence of di/dt limiting series reactors at the line terminals. The value of this series inductor is not that important as long as it is above 1 mH. Since the current flowing through the surge capacitor is proportional to the derivate of the voltage across the capacitor, a sharper change can be observed in the surge capacitor current when a voltage surge arrives at the terminal. The Rogowski coil output voltage, which is proportional to the derivate of the surge capacitor current, produces even sharper transient change at the arrival of a surge. Thus this proposed measuring scheme is an excellent method for detecting the travelling wave arrival times. The parameters of the Rogowski coil used in the study are given in Table-1.

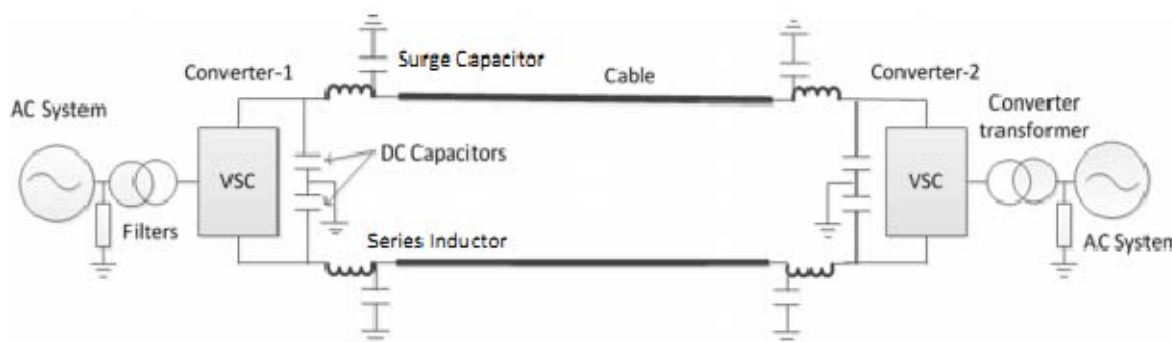


Figure 2: Test Network

Figure 3 shows how the currents and voltages observed in the test system for a solid pole-to-ground (P-G) fault occurring 130 km from the rectifier side of the 300 km cable. The fault was applied at 0.6s. Fault locations were calculated using the timing obtained by comparing the Rogowski coil output signals with a threshold. First, the system was calibrated by calculating the propagation velocity by applying a test fault at a known location (5 km from Converter-1). Then a number of different faults were simulated and the fault locations were calculated using Equation 1. The results are given in the Table 2. According to Table 2, calculated fault locations were reasonably accurate, with the maximum error 807 m for a fault applied 260 km away from Converter-1.

Inner radius	260 mm
Outer radius	284 mm
Resistance	468 Ω
Self-Inductance	3.5 mH
Capacitance	60.93 pF
Mutual-Inductance	0.55 μ H

Table 1: Parameters of the Rogowski coil used in the study

Actual fault	Errors (km)
Actual fault location (km)	Errors (km)
30	0.209
50	0.707
130	0.567
160	-0.394
230	-0.286
260	-0.807

Table 2: Fault location errors

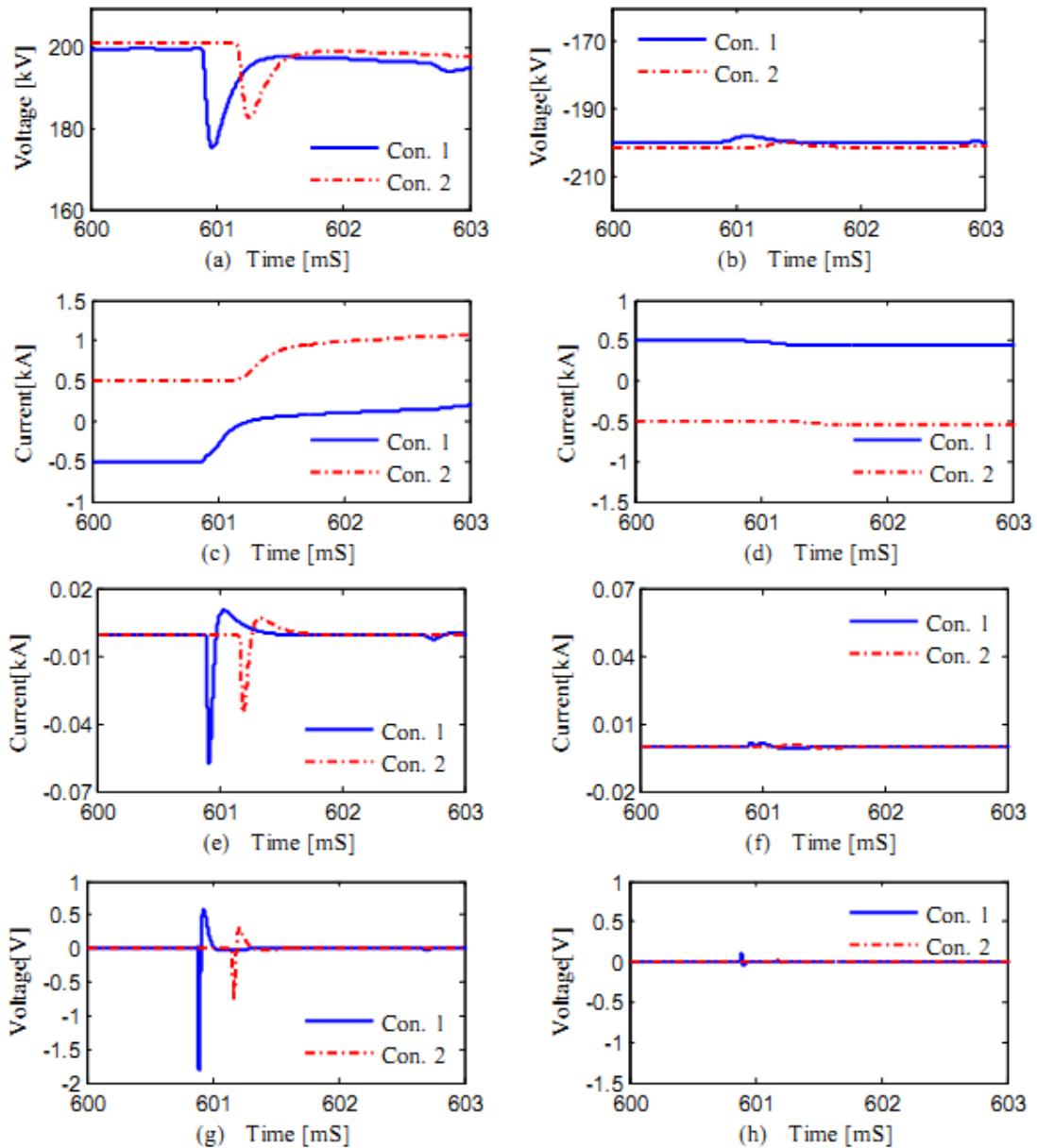


Figure 3: Variations of the terminal voltages (a) Positive poles (b) Negative poles, the terminal currents (c) Positive poles (d) Negative poles, the surge capacitor currents (e) Positive pole (f) Negative pole and the Rogowski coil voltages (g) Positive pole (h) Negative pole for solid pole-to-ground fault on positive pole 130 km from Converter-1.

4 EFFECT OF FREQUENCY ON VELOCITY OF THE TRAVELLING WAVE

Velocity of a travelling wave travelling along a transmission line u is given by:

$$u = \frac{2\pi f}{\text{Im}\{y\}} \quad \gamma = \sqrt{(R + j2\pi fL) \cdot (G + j2\pi fC)} \quad [2]$$

where y is the propagation constant, R is the series resistance per unit length of transmission line, L is the series inductance per unit length of transmission line, G is the conductance per unit length of transmission line, C is the capacitance per unit length of transmission line f is the frequency.

Unlike in the case for a lossless cable, the propagation velocity in a real cable with losses is frequency dependent as explained by Equation 2. Note that the R , L , C and G values in Equation 2 are also frequency dependent. The variation of the propagation velocity with frequency is dependent on the cable configuration and some examples can be found in [5]. The wave fronts generated by faults contain a range of frequencies, and due to frequency dependency of the propagation velocity, different frequency components arrives at the cable terminal at differing times. This behavior is called dispersion and is usually cause errors in the fault location calculation if the attenuation is high.

According to the observations after a fault close to Converter-1, the travelling wave arriving at Converter-1 has a wave front with a very sharp rising slope, and hence contains frequency components of higher order. The corresponding travelling wave arriving at Converter-2 is subjected to more attenuation along the line, and the wave front observed at Converter-2 terminal is characterized with a more gradual increase in the voltage. This happens as high frequency components are subjected to

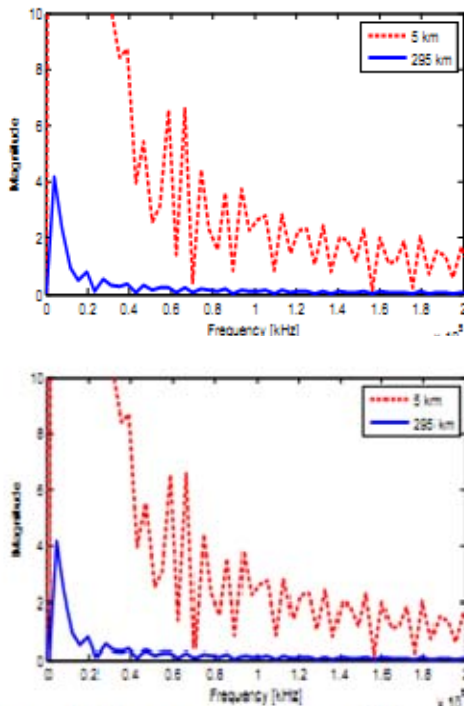


Figure 4: Frequency spectra of Rogowski coil voltages measured at the two ends

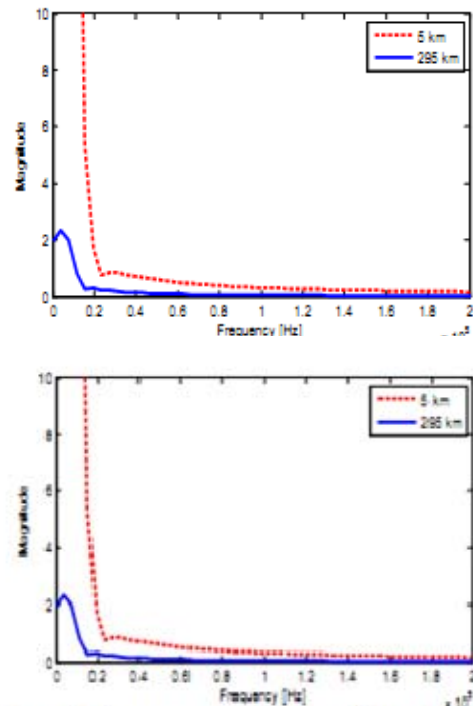


Figure 5: Frequency spectra of filtered Rogowski coil voltages measured at the two ends

In order to investigate whether filtering can improve the fault location accuracy, the signals used to detect the wave fronts (Rogowski coil voltages) were low pass filtered before comparing with the threshold. Accuracy of fault location was determined for faults at different locations with filtered signals. The experiments were repeated with filters having different cut-off frequencies (1 MHz, 500 kHz, 100 kHz, 50 kHz, and 10 kHz).

Solid pole-to-ground faults were simulated at six different locations. Fault location errors for different filter cut-off frequencies are shown in Table 3 and Table 4. Results shown in Table 3 and Table 4 shows that filtering improves the accuracy substantially. Initially the fault location accuracy improves when lowering the filter cut-off frequency. However, if the filter cut-off frequency is reduced below 50 kHz, the accuracy starts to decrease again. The best accuracies are obtained for the cut-off frequencies 100 kHz and 50 kHz.

Actual fault location (km)	Fault location error (km)					
	No filter	1MHz	500 kHz	100kHz	50kHz	10kHz
30	0.172	0.161	0.112	-0.095	0.071	0.159
50	0.707	0.641	0.576	0.163	0.114	-1.63
130	0.567	0.510	0.452	-0.004	0.030	-1.121
160	-0.394	-0.310	-0.190	-0.089	-0.015	1.164
230	-0.286	-0.278	-0.197	-0.203	-0.011	52.462
260	-0.807	-0.731	-0.619	-0.216	-0.129	67.948

Table 3: Fault location errors for solid pole-ground faults

Actual fault location (km)	Fault location error (km)					
	No filter	1MHz	500 kHz	100kHz	50kHz	10kHz
30	-0.088	-0.136	-0.117	0.058	0.140	0.804
50	0.427	0.362	0.359	0.206	0.129	-2.195
130	0.474	0.380	0.182	-0.003	0.011	-1.510
160	-0.182	-0.172	-0.164	-0.071	0.012	1.723
230	-0.100	-0.056	-0.068	-0.135	0.064	53.374
260	-0.499	-0.424	-0.414	-0.204	-0.152	68.969

Table 4: Fault location errors for pole-ground faults with fault resistance 100 Ω

5 CONCLUSION

Fault location in a VSC HVDC line was investigated using test system simulated in PSCAD/EMTDC. A method for detecting wave front arrival times required for travelling wave based fault location was proposed. The results of this simulation experiment showed that filtering of the detection signals using a low pass filter with a cutoff frequency in the range of 50-100 kHz improves the fault location accuracy. When the signals measured at the both ends are band limited to the same highest frequency, surge arrival time differences can be measured more accurately. Cut-off frequency of the filter used in this test network may not be the optimum for another system with a different cable length since the amount of attenuation depends on the cable length. Suitable filter parameters for a given system can be easily determined using simulations performed an EMT program such as PSCAD/EMTDC with accurate cable models.

REFERENCES

- [1] E. O. Schweitzer. "A Review of Impedance-Based Fault Locating Experience" Proceedings of the 15th Annual Western Protective Relay Conference, Spokane, WA, October 24-27, 1988.
- [2] U. A. Bakshi and A. P. Godse. Analog Communication, Technical Publications Pune, 2009.
- [3] P. Cheng, B. Xu, J. Li. "A travelling wave based fault locating system for HVDC transmission lines" 2006 International Conference on Power System Technology, Chongqing, October 2006.
- [4] M. M. Saha, J. Izykowski and E. Rosolowski. Fault Location on Power Networks, Springer Verlag, 2009.
- [5] L. M. Wedepohl and D. J. Wilcox. "Transient analysis of underground power transmission systems - System model and wave-propagation characteristics" Proceedings of Institution of Electrical Engineers, Vol. 120, No. 2, February 1973.