WAVELET TRANSFORM BASED FAULT LOCATION ESTIMATOR FOR STATCOM COMPENSATED LINES

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ABSTRACT
Voltage Source Converter (VSC) based Flexible AC Transmission system (FACTS) controllers have several advantages like modular construction, better performance, facility to add an energy source at the DC bus. Static Synchronous Compensator (STATCOM) is a VSC based shunt connected controller employed to have better voltage regulation at critical buses. A STATCOM with energy storage device facilitates operation in any of the four quadrants and hence present methods for fault location estimation may not be accurate and reliable. This paper puts forward a new, simple and dependable wavelet transform based fault location estimator for transmission lines deploying STATCOM integrating energy storage device. It is shown that the recommended estimation methodology is very precise and is least affected by operating mode of STATCOM and fault resistance.

Key words: Wavelet transform, STATCOM, Energy storage, Fault location.

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1. INTRODUCTION
A large proportion of the power system faults are transmission line faults. Main/primary transmission lines generally are long transmission lines covering few hundreds of kilometers [1]. Long transmission lines customarily employ series and/or shunt compensation to improve
power transfer, stability margin and voltage regulation [2,3]. Accurate estimation of fault location in such lines is a challenging task. Accurate estimation of location of fault on the line reduces the burden on the operating personnel and the faulty line can be quickly restored to service. Various methods and practical aspects to predict the fault distance are outlined in “IEEE guide for determining fault location on AC transmission and distribution lines” [4]. Fundamental problems with respect to accurate estimation of transmission line fault location is discussed in [5] and a comparison of three algorithms for fault location prediction is presented. Effect of fault impedance, fault location etc. on impedance based fault distance determination techniques is studied in [6]. A method to increase the efficiency of impedance based fault location estimator using digital fault recorders is described by Saeed et al. [7]. Post fault one terminal voltage data is used to determine the fault location by Carlos and Louis [8]. Xiangning et al. [9] proposed a generalized method to enhance the efficacy of fault location estimation algorithms based on lumped parameter model and one terminal data. Fault location estimation method based on synchronized voltage measurements at the two ends of the line is reported by Sukumar and Adly [10]. These articles cover various fault location estimation methods for uncompensated lines. Few researchers have reported their findings on fault location methods for series and/or shunt compensated lines. Various methods are proposed for fault location in fixed series compensated lines [11, 12, 13]. A non-iterative algorithm based on synchronous voltage and current signals from both the ends of the line is proposed by Mahdi and Javad [14] to estimate fault location in lines compensated by TCSC and TCR. Methods described for fault location estimation in [11-14] do not consider VSC based FACTS controllers.

The transient current and voltage signals after the occurrence of short circuit line faults contain various frequency components which can be utilized for fault detection and fault location estimation. Researchers have shown great interest in wavelet transform based methods to detect line faults and predict distance of fault from relay point. “Summation of wavelet detail coefficients is used for fault detection and classification” in [15]. However, the method is not immune to fault resistance and does not cover fault location prediction. In [16], line faults are identified, categorized and fault distance is predicted employing combined wavelet transform and ANN based technique.

Very little reported work is available on wavelet transform based fault location estimation methods for transmission lines compensated with VSC based FACTS controllers. In [17], DWT based technique is employed for fault distance prediction in SSSC compensated lines. Only three phase fault is considered and the method is not very accurate. “Wavelet entropy based method is proposed for the detection and classification of lines compensated with SSSC and UPFC” in [18]. However, exact fault location is not determined. “Detection and classification of transmission line faults in the presence of STATCOM using wavelet based summation index” is described in [19]. Fault distance is not predicted. Hardly any reported work is available on fault location estimation in lines incorporating FACTS controllers incorporating energy storage device. “A wavelet transform based fault detection and fault location estimation method for lines compensated with SSSC incorporating energy storage device” is proposed in [20]. An appropriate and accurate fault location estimator for lines incorporating STATCOM with energy storage systems is not taken up for study and is proposed for the first time in this paper.

2. WAVELET TRANSFORM

Frequency domain methods have attracted power system researchers in detecting and categorizing various power system transients. However, for analyzing non-stationary signals during line faults, time information regarding frequency contents in the signal is essential. Short time Fourier transform (STFT) is very useful tool to get the frequency information from a
signal, localized in time. However, main drawback of STFT is its fixed window length and we will not be able to obtain simultaneously a better time and frequency resolution. Hence a different set of building blocks called wavelets are used to analyze such non-stationary signals. A wavelet can be translated forward or backward in time and can also be compressed or stretched to obtain high and low frequency wavelets. Essentially a wavelet transform adjusts its window length automatically i.e. it uses a narrow window for high frequencies and wide window for small frequencies. Thus wavelets are considered to be better in extracting high frequency components present in current and voltage signals during fault and a suitable relay logic can be developed for fast and reliable protection of transmission lines.

Discrete wavelet transform (DWT) is based on sub band coding. Advantages of DWT are fast computation and easy implementation [21]. In the case of DWT, wavelet coefficients are obtained as outputs from successive low pass and high pass filters of the discretized signal. Choosing a suitable mother wavelet is very important in wavelet analysis. “Daubechies (DB) mother wavelets are shown to be ideal for fault detection since they are fast, stable and accurate” [22]. Thus, in the current study, DB5 is used as the mother wavelet.

3. TEST SYSTEM

![Figure 1 SMIB system with STATCOM-ES](image_url)

Fig. 1 shows the test system adapted from IEEE first benchmark model which is a single machine connected to infinite bus with combined series and shunt compensated transmission line. \(V_g\angle\theta_g\), \(V_s\angle\theta_s\) and \(E_b\angle\theta_b\) are voltages at generator terminal, STATCOM bus and the infinite bus respectively. \((R_t + jX_t)\) is the impedance of the line transformer. \(X_c\) is the reactance of series capacitor. \((R_s + jX_s)\) is the impedance of the converter transformer. \(X_{sys}\) is the system reactance on the infinite bus side. The transmission line is divided into four PI sections.

3.1. System Equations

System is modeled in DQ frame of reference.

Magnitude of converter output voltage,

\[
V_s^l = \sqrt{V_{sq}^l \quad + \quad V_{sd}^l}^2
\]

where \(V_{sq}^l = K_m \quad V_{dc} \quad Sin(\theta_s + \alpha)\) 

\(V_{sd}^l = K_m \quad V_{dc} \quad Cos(\theta_s + \alpha)\)

Where \(K_m = K cos\beta; \quad K = \frac{2\sqrt{3}}{\pi}\) for a 12 pulse converter and
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\[ \theta_s = \tan^{-1}\left(\frac{V_{sd}}{V_{sq}}\right) \]  

(4)

Magnitude of STATCOM bus voltage,

\[ V_s = \sqrt{V_{sq}^2 + V_{sd}^2} \]  

(5)

System equations in D-Q variables,

\[ \frac{di_{sd}}{dt} = -\frac{R_s}{x_s} i_{sd} - \omega_0 i_{sq} + \frac{\omega_B}{x_s} [v_{sd} - v_{si}^i] \]  

(6)

\[ \frac{di_{sq}}{dt} = -\frac{R_s}{x_s} i_{sq} + \omega_0 i_{sd} + \frac{\omega_B}{x_s} [v_{sq} - v_{si}^i] \]  

(7)

In phase and quadrature components of STATCOM current,

\[ I_p = I_{sd} \sin \theta + I_{sq} \cos \theta \]  

(8)

\[ I_r = -I_{sd} \cos \theta + I_{sq} \sin \theta \]  

(9)

Here ‘\( \theta \)’ is the angle of STATCOM current.

When \( I_p \) is positive STATCOM takes active power and it provides power to the connected system when \( I_p \) is negative. Positive \( I_r \) indicates that STATCOM – ES is in inductive mode.

Power drawn by STATCOM,

\[ P_s = I_{sd} * V_{sd}^i + I_{sq} * V_{sq}^i \]  

(10)

\[ Q_s = I_{sq} * V_{sd}^i - I_{sd} * V_{sq}^i \]  

(11)

3.2. Quadrants of operation of STATCOM-ES

A STATCOM with energy storage device can inject real current in addition to reactive current. Hence operating region of STATCOM-ES is wide-ranging and can be in any of the four quadrants shown in Fig. 2.

![Figure 2 Operating range of STATCOM-ES](https://ssrn.com/abstract=3658077)

Operating modes of STATCOM – ES is described below.

- I quadrant: Inductive mode, taking active power; ‘\( \theta_{st} \)’ is between 0° and 90°.
- II quadrant: Inductive mode, providing active power; ‘\( \theta_{st} \)’ is between 90° and 180°.
- III quadrant: Capacitive mode, providing active power; ‘\( \theta_{st} \)’ is between -90° and 180°.
• IV quadrant: Capacitive mode, taking active power; ‘θ_{st}’ is between 0° and -90°.

In case of STATCOM with energy storage device type 1 controller is used to facilitate control of both |V_S| and α [23].

4. METHODOLOGY

The power system current signals at the relay location are sampled at a rate of 24kHz i.e. 400 samples per cycle. With DB5 as mother wavelet, currents I_a, I_b, and I_c are passed through wavelet filters to obtain approximated and detail coefficients. Summation fault index for I_a, I_b, and I_c are determined using wavelet detail coefficient at level 3. Simulation study is carried using MATLAB/SIMULINK.

4.1. Fault detection

L1 norm summation fault index using reconstructed current signals I_a, I_b, and I_c from wavelet detail coefficients at level 3 is computed as described by eq. (12) for current I_a.

\[ F_{I_a} = \sum_{n=1}^{N} |D3I_a(n)| \]  

Similarly, F_{I_b} and F_{I_c} are determined for currents I_b and I_c. Here ‘N’ is taken as 200 i.e. number of samples per half cycle of power frequency. Summation fault index are computed for every half cycle of power frequency and the values obtained immediately after the occurrence of fault is compared with suitable threshold to identify and categorize faults.

4.2. Fault location estimation

To estimate fault location, for known fault distance from the relay point, wavelet based summation fault indices are determined. From the plot of fault location versus fault index, using curve fitting tool of MATLAB, best fit (4th degree polynomial) equations are obtained to estimate the distance of line fault from the relay location (Y) using wavelet transform based fault indices (x). The polynomials for fault location prediction, with various fault types are given by equations (13 to 16). Please note that in equations 13 to 16, fault indices for I_b, F_{I_1b} is utilized to get the 4th degree polynomial for fault location prediction, as in these faults B is a faulty phase. Fault location prediction polynomials for other faults are obtained using similar methodology.

Three phase fault

\[ Y = 3.4166 \times 10^5 x^4 - 1.9361 \times 10^5 x^3 + 41788x^2 - 4306.7x + 202.51 \]  

LLG (ABG) fault

\[ Y = 3.6475 \times 10^5 x^4 - 1.9689 \times 10^5 x^3 + 40444x^2 - 3983.1x + 182.11 \]  

LL (AB) fault

\[ Y = 7.0631 \times 10^5 x^4 - 2.8061 \times 10^5 x^3 + 42725x^2 - 3236.4xx + 124.37 \]  

SLG (BG) fault

\[ Y = 4.9387 \times 10^5 x^4 - 2.5591 \times 10^5 x^3 + 50212x^2 - 4669x + 197.67 \]  

Error in fault location prediction is determined using eq. (17).

\[ \text{Error in } \% = \frac{\text{Predicted fault distance} - \text{Actual fault distance}}{\text{Line length}} \times 100 \]  

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5. RESULTS AND DISCUSSION
Wavelet transform based fault location estimator described in section 4 is tested by considering symmetrical and unsymmetrical faults on the line. Faults are considered up to 80%–line length, considering relay zone 1 reach to be 80%. Using equations 13 to 16, distance of short circuit fault on the line from the relay point is estimated. Table 1 shows the obtained result. Predicted values of fault location shown in Table 1 endorse that the wavelet transform based fault location estimator is able to estimate the fault location very accurately and the highest error in estimation is less than 0.6%. From the plot of estimated fault location shown in fig. 3, it is inferred that the wavelet transform based fault location estimator is very accurate in predicting the location of fault, irrespective of the fault type.

Table 1 Estimated fault location, STATCOM compensated system

| Fault location (actual in %) | Fault location (Estimated in %) |
|-----------------------------|---------------------------------|
|                            | Fault type                      |
|                            | Three phase | ABG | AB | BG |
| 10                          | 10.049       | 10.049 | 10.055 | 10.035 |
| 15                          | 14.713       | 14.705 | 14.718 | 14.668 |
| 20                          | 20.338       | 20.372 | 20.342 | 20.428 |
| 25                          | 25.193       | 25.204 | 25.195 | 25.202 |
| 30                          | 29.848       | 29.833 | 29.849 | 29.775 |
| 40                          | 39.605       | 39.587 | 39.608 | 39.534 |
| 50                          | 49.874       | 49.886 | 49.885 | 49.899 |
| 60                          | 60.317       | 60.341 | 60.315 | 60.395 |
| 65                          | 65.345       | 65.376 | 65.349 | 65.429 |
| 70                          | 70.246       | 70.269 | 70.242 | 70.294 |
| 75                          | 74.976       | 74.981 | 74.973 | 74.966 |
| 80                          | 79.531       | 79.49  | 79.531 | 79.427 |
| Maximum Error (%)           | -0.469       | -0.51  | -0.469 | -0.573 |

Figure 3 Estimated fault location without STATCOM
5.1. Influence of operating mode of STATCOM on fault location prediction

Fault location estimation equations 13 to 16 and the estimated values shown in Table 1 are for the test system without STATCOM. STATCOM with energy storage device, as discussed in section 3.2, can operate in 4 quadrants with wide operating range. Obtaining best fit equations for every possible operating mode of STATCOM – ES is almost impossible. Thus, regardless of the operating mode of STATCOM – ES, equations 13 to 16 are used to calculate the fault distance, depending on the fault type. Efficiency of the proposed fault location predictor is evaluated by considering different quadrants of operation of STATCOM – ES.

Table 2 Influence of operating mode of STATCOM

| Fault location(actual) in % | Fault location(Estimated) in percentage | Maximum error (%) |
|---------------------------|----------------------------------------|-------------------|
| No STATCOM                | Q_s = -0.1625, P_{ref} = 0             | -0.482            |
| 15                        | 14.718                                 | 14.755            |
| 30                        | 29.849                                 | 29.797            |
| 45                        | 44.734                                 | 44.518            |
| 60                        | 60.315                                 | 60.368            |
| 75                        | 74.973                                 | 75.673            |

Table 2 shows the sample result obtained for double line fault (AB) with various operating modes of STATCOM – ES which clearly indicates that the inaccuracy in fault location prediction with various operating modes of STATCOM – ES is negligible.

5.2. Effect of fault resistance (R_F) on fault location estimation

The computed value of Z_{relay} in the case of distance relay is modified considerably with the change in the value of R_F. Hence fault location estimators based on computed impedance may not be reliable. To study the influence of R_F on the efficacy of proposed fault location estimator, fault distance is predicted with increasing values of fault resistance for different fault type, fault location and operating mode of STATCOM – ES. Table 3 shows the obtained result.

Table 3 Effect of R_F

| Fault location (%) | Operating mode | Fault type          | Estimated fault location (%) |
|--------------------|----------------|---------------------|------------------------------|
| 30                 | No STATCOM     | Symmetrical         | R_F = 0 Ω 29.847 29.818 29.789 |
| 50                 | Q_s = 0, P_{ref} = -0.15 | LL (AB)             | R_F = 5 Ω 49.266 49.238 49.209 |
| 75                 | Q_s = -0.11094, P_{ref} = 0.1 | SLG (BG)           | R_F = 10 Ω 75.561 75.502 75.443 |

It is encouraging to note from Table 3 that, in case of wavelet based relay, error in estimation of fault distance corresponding to increase in the value of R_F is insignificant.

6. CONCLUSION

A novel wavelet transform based method is described in this work to estimate the location of fault on transmission line incorporating STATCOM with energy storage device. The proposed method uses currents at one terminal. It is simple, reliable and very accurate. Computation time for fault index is very less since wavelet transform based L1 norm summation fault index is used. The error in fault location prediction considering operation of STATCOM in any of the four quadrants and with higher values of fault resistance is insignificant. Accurate estimation...
of faults in shunt compensated lines will help the power system engineers to quickly restore the faulty line into service.

REFERENCES

[1] Ravindra P. Singh, *Digital Power System Protection*, PHI, 2007.
[2] K.R. Padhyar, *FACTS controllers in Power transmission and Distribution*, New Age International, 2008.
[3] N.G. Hingorani and L. Gyugyi, *Understanding FACTS*. New York: IEEE press, 2000.
[4] IEEE Guide for Determining Fault Location on AC Transmission and Distribution lines, 2005. *IEEE Std. 37.114-2004*.
[5] Cook V., “Fundamental aspects of fault location algorithms used in distance protection”, *in Proc, IEE*, vol.137, no.6, pp. 359- 368, 1986.
[6] Dalcastagnê, A.L., Zimath, S.L, “A study about the sources of error of impedance-based fault location methods”, *IEEE/PES Transmission and Distribution Conference and Exposition*: Latin America, T and D-LA, 2008
[7] Saeed Roostaee, Mini S. Thomas and Shabana Mehfuz, “Experimental studies on impedance based fault location for long transmission lines”, *Protection and Control of Modern Power Systems*, pp. 2 – 16, Apr.2017
[8] Eduardo De C., Pereira M. and Zanetta L. C., “Fault location in transmission lines using one terminal post fault voltage data”, *IEEE Transactions on Power Delivery*, vol.19, No.2, pp 570-575, 2004
[9] Xiangning Lin, Hanli weng and Bin Wang, “A generalized method to improve the location accuracy of the single-ended sampled data and lumped parameter model based fault locators”, *Electrical Power and Energy Systems*, vol.31, no.5, pp 201-205, 2009.
[10] Brahma S.M. and Girgis A.A., “Fault location on a transmission line using synchronized voltage measurements”, *IEEE Transactions on Power Delivery*, vol.19, No.4, pp.1619-1622, 2004.
[11] J. Sadeh, N. Hadjsaid, A. M. Ranjbar, and R. Feuillet, “Accurate fault location for series compensated transmission lines”, *IEEE Transactions on Power Delivery*, vol.15, no. 3, pp. 1027–1033, Jul. 2000.
[12] M. Al-Dabbagh and S. K. Kapuduwage, “Using instantaneous values for estimating fault locations on series compensated transmission lines,” *Electrical Power System. Research*, vol. 76, pp. 25–32, 2005.
[13] Swetapadma, A., Yadav, A., “A hybrid method for fault location estimation in a fixed series compensated lines” *Measurement* *Journal of the International Measurement Confederation*, vol. 123, pp. 8-1, Jul. 2018.
[14] Mahdi Ghazizadeh Ahsae and Javad Sadeh, “A Novel Fault-Location Algorithm for Long Transmission Lines Compensated by Series FACTS Devices”, *IEEE Transactions on Power Delivery*, Vol. 26, NO. 4, October 2011.
[15] Valsan S.P, Swamy K.S, “Wavelet transform based digital protection for transmission lines”, *International journal of electrical power and energy systems*, vol.31, Issue 7-8, pp. 379 – 388, sept.2009.
[16] Jaya Bharata reddy, M. Venkata Rajesh, D. Mohanti, “Robust transmission line fault classification using wavelet multi resolution analysis”, *Computer and electrical Engineering*, vol.39, Issue 4, pp.1219 – 1227, May 2013.
[17] Geetanjali M, Alias M.A, Pandy T.K.S, “Discrete wavelet transform based fault detection and classification in a static synchronous series compensated transmission system”, *Advances in intelligent systems and computing*, vol.258, pp. 85 – 94, 2014.
[18] El. Zankoly A.M, Desovic H, “Wavelet entropy based algorithm for fault detection and classification in FACTS compensated transmission lines”, *International journal of electrical power and energy systems*, vol.33, Issue 8, pp.1368 – 1374, October 2011.

[19] Rao P. V, Gefoor S.A, Venkatesh, “Detection of transmission line faults in the presence of STATCOM using wavelets”, *IEEE India conference, INDICON* 2011, December 2011.

[20] H.V Gururaja Rao., Prabhu, N. & Mala, R.C. Wavelet transform-based protection of transmission line incorporating SSSC with energy storage device. *Electr Eng* (2020). https://doi.org/10.1007/s00202-020-00978-9

[21] Valsan S.P, Swamy K.S, “Wavelet transform based digital protection for transmission lines”, *International journal of Electrical Power and Energy Systems*, vol.31, Issue 7-8, pp. 379 – 388, Sept. 2009.

[22] Jittiphong Klomjit, Atthapol Ngapitakkul, Bancha Sreewirote, “Comparison of mother wavelet for classification fault on hybrid transmission line systems”, *IEEE 8th International Conference on Awareness Science and Technology (iCAST)*, Taiwan, November 2017.

[23] H.V. Gururaja Rao, Dr. Nagesh Prabhu, R.C. Mala, “Impact of real and reactive power controllability of STATCOM on transmission line protection”, International Journal of Electrical Engineering & Technology (IJEEET), Volume 10, Issue 3, May -June 2019, pp. 21-35, https://doi.org/10.34218/ijeet.10.3.2019.004

[24] B. K. N. Srinivasa Rao and P. Sowmya, Architectural Implementation of Video Compression Through Wavelet Transform Coding and Ezw Coding. International Journal of Electronics and Communication Engineering & Technology (IJECET), Volume 3, Issue 2, October- December (2012), pp. 202-210.

[25] Geetha H S and Rehna V J, Bibliographical Survey for a Novel Approach Towards Development of a Hybrid Approach of Image Coding Using Neural Network and Wavelet Transform. International Journal of Electronics and Communication Engineering & Technology (IJECET), Volume 5, Issue 5, May (2014), pp. 36-42.

**APPENDIX**

System Data (Base MVA = 892.4, Base Voltage = 500 kV).

Generator data (All values in pu)

Ra = 0; Xd = 1.79;Xd = 1.71; Xd’ = 0.169; Xd” = 0.135; Xq = 0.228; Xq’ = 0.228; Xq’’ = 0.2; Td’ = 0.4; Td” = 0.0259; Td’’ = 0.1073; Td”’ = 0.0463; f = 60; H = 5; D = 0;

Transmission system data (All values in pu)

Rt = 0.0; Xl = 0.14; Zl,1 = 0.04 + j1; Zd = 0.08 + j2; Xc = 0.45; XSYS = 0.06; Ve = Vd<0; Ee =1<0;

STATCOM data

150MVA; Rs = 0.01 pu; Xs = 0.15 pu; Vdc = 0.7 pu