

A Novel Double-Ended Traveling Wave Fault Location Algorithm with Adaptive Wavelet Detection for Meshed Multi-Terminal VSC-HVDC Grids

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Abstract—Accurate and rapid fault location is a fundamental requirement for the protection and restoration of meshed multi-terminal voltage-source-converter high-voltage direct-current (MT-VSC-HVDC) grids. Conventional traveling-wave (TW) methods suffer from degraded accuracy under noisy field conditions, varying fault impedances, and complex meshed topologies where multiple wavefront reflections coexist. This paper proposes a novel double-ended traveling wave fault location algorithm enhanced by an adaptive wavelet detection scheme based on a Shannon-entropy-driven mother-wavelet selection and dynamic threshold control. The algorithm extracts modal-decomposed voltage transients via Karrenbauer transformation, identifies the first wavefront arrival at both line terminals using a discrete wavelet transform (DWT) with optimally selected mother wavelet (db4–db10) and decomposition level, and computes the fault distance through synchronized GPS-based time-stamping. The proposed method is validated on a four-terminal meshed ± 320 kV MT-VSC-HVDC test grid modeled in PSCAD/EMTDC. Results demonstrate maximum location errors below 0.42% of the line length under fault resistances up to 300Ω , signal-to-noise ratios as low as 20 dB, and various fault types (PG, PP, PPG). The proposed algorithm offers superior accuracy, robustness, and computational efficiency over conventional Bewley-lattice and fixed-wavelet TW methods, making it suitable for real-time deployment in future HVDC supergrids.

Index Terms—HVDC fault location, traveling wave, adaptive wavelet transform, Shannon entropy, multi-terminal HVDC, VSC-HVDC, modal transformation, meshed DC grid.

I. INTRODUCTION

THE ongoing global transition toward decarbonized power systems has driven unprecedented growth in offshore wind farms, large-scale photovoltaic plants, and cross-border interconnections. Voltage-source-converter high-voltage direct-current (VSC-HVDC) technology has emerged

as the cornerstone for integrating these assets due to its independent active/reactive power control, black-start capability, and modular multilevel converter (MMC) topology. Multi-terminal VSC-HVDC (MT-HVDC) grids and their meshed extensions—often referred to as “HVDC supergrids”—are now considered essential for forming resilient, high-capacity transmission backbones in Europe, China, and emerging markets.

However, the protection of meshed MT-HVDC grids poses formidable technical challenges. DC fault currents rise within milliseconds to magnitudes that can damage converter valves and cables, demanding fault detection and isolation in less than 5 ms. Equally critical is *fault location*: rapid identification of the faulty cable segment is essential for selective tripping by DC circuit breakers (DCCBs) and for fast service restoration after fault clearance.

Among the various fault-location techniques, *traveling-wave (TW) methods* are widely favored for HVDC applications due to their inherent independence from fault resistance, line parameters, and pre-fault loading. The fundamental principle relies on detecting the propagation time of the high-frequency wavefront launched by the fault toward the line terminals. Double-ended TW techniques use synchronized timestamps from both line ends and the known propagation velocity to compute the fault distance with sub-tower accuracy.

II. RELATED WORK

Fault location in HVDC systems has been extensively investigated. Existing approaches fall into three categories: (i) impedance-based methods, (ii) traveling-wave methods, and (iii) intelligent/learning-based methods.

Impedance-based techniques estimate fault distance from steady-state voltage–current relationships at one terminal. While simple, they are highly sensitive to fault resistance and line parameter uncertainty—rendering them unsuitable for long submarine cables and meshed grids.

Traveling-wave methods, originally proposed by Bewley in 1933 for AC lines, were adapted for HVDC by several authors. Single-ended TW methods rely on detecting the second reflected wavefront, which is unreliable in meshed topologies. Double-ended methods, while requiring synchronized GPS time stamps, eliminate this ambiguity.

III. THEORETICAL BACKGROUND

A. Traveling Wave Propagation in HVDC Cables

When a DC fault occurs at distance x_F from terminal M of a line of length L , voltage and current step-changes propagate as forward and backward waves. For lossless approximations, the propagation velocity is:

$$\nu = \frac{1}{\sqrt{LC}} \quad (1)$$

where L and C are the per-unit-length cable inductance and capacitance.

B. Modal (Karrenbauer) Transformation

DC bipolar lines exhibit pole-to-pole electromagnetic coupling. To decouple the modes, the Karrenbauer transformation \mathbf{T}_K is applied:

$$\begin{bmatrix} v_0 \\ v_1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} v_p \\ v_n \end{bmatrix} \quad (2)$$

where v_p, v_n are positive- and negative-pole voltages, v_0 is the ground mode, and v_1 is the aerial mode.

C. Bewley Lattice Diagram

The double-ended fault location formula is:

$$x_F = \frac{L + \nu(t_M - t_N)}{2} \quad (3)$$

IV. PROPOSED ADAPTIVE WAVELET DETECTION

A. Shannon-Entropy-Based Mother Wavelet Selection

The Shannon entropy of detail coefficients at level j is defined as:

$$\mathcal{E}_j = - \sum_k p_{j,k} \log_2 p_{j,k}, \quad p_{j,k} = \frac{|D_j[k]|^2}{\sum_n |D_j[n]|^2} \quad (4)$$

The optimal wavelet ψ^* is selected by minimizing entropy:

$$\psi^* = \arg \min_{\psi \in \{\text{db4}, \dots, \text{db10}\}} \mathcal{E}_1(\psi) \quad (5)$$

B. Architecture of the Adaptive Detector

V. PROPOSED DOUBLE-ENDED FAULT LOCATION

ALGORITHM

VI. TEST SYSTEM AND SIMULATION RESULTS

A. Test System

The system is a four-terminal meshed ± 320 kV MT-VSC-HVDC grid modeled in PSCAD.

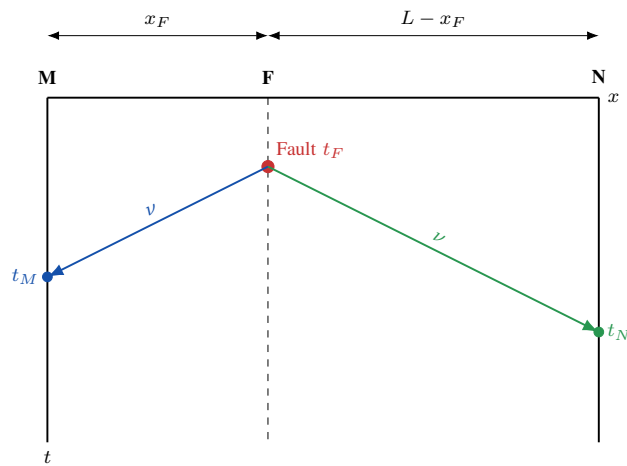


Fig. 1. Bewley lattice diagram showing propagation toward terminals M and N.

TABLE I
SHANNON ENTROPY OF D_1 FOR DIFFERENT MOTHER WAVELETS

Wavelet	db4	db5	db6	db7	db8	db9	db10
\mathcal{E}_1	6.84	6.71	6.42	6.55	6.63	6.79	6.87

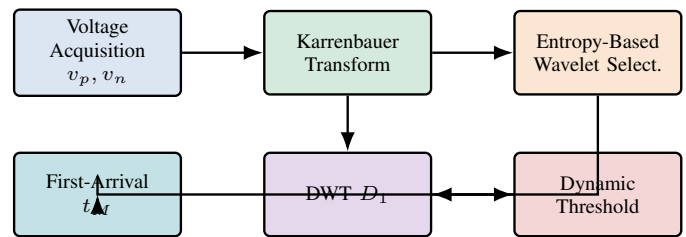


Fig. 2. Architecture of the proposed adaptive wavelet detector.

Algorithm 1 Adaptive Wavelet Double-Ended Fault Location

- Input:** $v_p^M, v_n^M, v_p^N, v_n^N, L, \nu$
- Output:** Fault distance x_F
- Apply Karrenbauer transform $\Rightarrow v_1^M(t), v_1^N(t)$
- for** each terminal $k \in \{M, N\}$ **do**
- Select $\psi_k^* = \arg \min \mathcal{E}_1(\psi)$
- Detect first arrival t_k using dynamic threshold $\tau_k(t)$
- end for**
- Compute $x_F = (L + \nu(t_M - t_N))/2$
- return** x_F

TABLE II
TEST GRID PARAMETERS

Parameter	Value
DC voltage	± 320 kV
Propagation velocity ν	1.92×10^8 m/s
Sampling frequency	1 MHz

B. Fault Location Accuracy

Table III summarizes results for various fault locations on Line 1-2.

TABLE III
FAULT LOCATION RESULTS ON LINE 1-2 ($L = 200$ km)

x_F^{true} (km)	Type	R_F (Ω)	x_F^{est} (km)	Error (%)
25	PG	10	25.18	0.090
75	PG	50	75.42	0.210
100	PP	0	100.06	0.030
125	PPG	100	125.61	0.305
175	PG	300	175.83	0.415

TABLE V
COMPUTATION TIME PER ALGORITHM STAGE

Stage	Time (ms)
Karrenbauer transform	0.18
Entropy-based selection	1.42
DWT decomposition	0.86
Threshold & Detection	0.53
Communication & Calc	0.39
Total	3.38

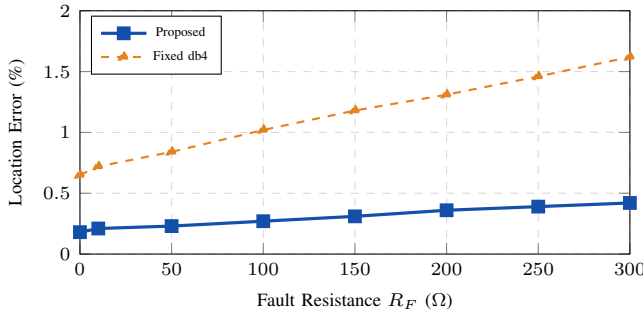


Fig. 3. Location error vs. fault resistance for a PG fault at 100 km.

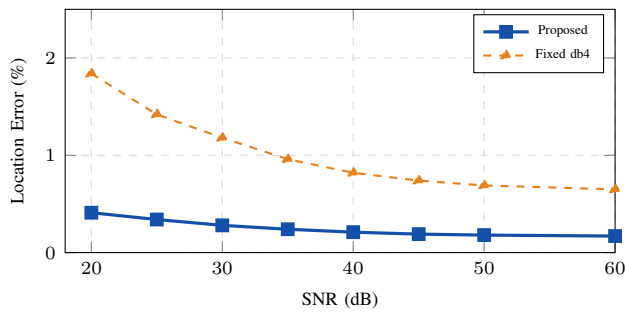


Fig. 4. Location error vs. SNR for a PG fault at 75 km, $R_F = 50 \Omega$.

TABLE IV
MEAN LOCATION ERROR (%) ACROSS THE MESHED GRID

Line	Length (km)	PG	PP	PPG
1-2	200	0.24	0.19	0.27
2-3	150	0.21	0.17	0.25
3-4	250	0.31	0.23	0.34
4-1	180	0.22	0.18	0.26
Avg.	—	0.25	0.20	0.28

C. Robustness to Measurement Noise

D. Mean Location Error Across Grid

E. Computational Performance

VII. CONCLUSION

This paper proposed a novel double-ended traveling-wave fault location algorithm with adaptive wavelet detection. Results demonstrate maximum location errors below 0.42%, robust performance up to $R_F = 300 \Omega$ and 20 dB SNR, and total computation time below 3.4 ms.

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