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Faulted-Branch Identification and High-Impedance Fault Location in Multi-Terminal HVDC Transmission Networks using Modal Traveling Wave Analysis

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Abstract*—Multi-terminal high-voltage direct-current transmission systems are increasingly being adopted for large-scale renewable integration, offshore wind collection, and asynchronous grid interconnection. However, protection of multi-terminal HVDC networks is challenging due to low line impedance, fast-rising fault currents, absence of natural current zero crossing, and complex propagation of traveling waves across junctions and converter terminals. High-impedance faults further complicate protection because their current magnitudes may be comparable to normal operating transients, making conventional overcurrent and differential schemes less reliable. This paper presents a modal traveling wave based method for faulted-branch identification and high-impedance fault location in multi-terminal HVDC transmission networks. The proposed method decomposes pole-domain voltage/current signals into modal components, detects initial wavefront arrival times using energy-based wavelet processing, identifies the faulted branch through polarity and arrival-time consistency, and estimates the fault distance using modal propagation velocity. A four-terminal meshed HVDC network is considered for analysis. Simulation-based results show that the proposed method can identify the faulted branch rapidly and locate high-impedance faults with acceptable accuracy under different fault resistances, fault locations, and sampling frequencies. The method is suitable for fast primary protection of future DC grids.

***Index Terms*—HVDC protection, multi-terminal HVDC, high-impedance fault, traveling wave, modal transformation, fault location, DC grid protection.**

I. INTRODUCTION

High-voltage direct-current (HVDC) transmission has become an important technology for long-distance bulk power transfer, offshore wind integration, interconnection of asynchronous AC grids, and enhancement of power-system controllability. Voltage-source converter based HVDC systems are particularly attractive for multi-terminal configurations because of their independent control of active and reactive power, black-start capability, and flexibility in connecting weak AC systems.

Protection of multi-terminal HVDC grids is significantly more difficult than that of conventional AC networks. DC faults produce rapidly increasing currents because the line resistance and inductance are low and because power-electronic converters can feed fault currents through freewheeling diodes or converter control actions. Unlike AC systems, DC systems do not have natural current zero crossings, making interruption more difficult. Therefore, fault detection, faulted-branch identification, and fault location must be performed within a few milliseconds.

Among different protection techniques, traveling wave based protection is promising because fault-generated voltage and current surges propagate at nearly the speed of light along transmission lines. By measuring the arrival time, polarity, and magnitude of these waves at line terminals, the faulted section and fault distance can be estimated rapidly. However, in multi-terminal HVDC systems, traveling waves are reflected and refracted at junctions, line terminations, and converter stations, making faulted-branch identification more complex.

High-impedance faults are especially challenging because the fault current may be limited by the fault resistance, ground path, or arc impedance. Such faults may not produce sufficiently large current magnitudes for traditional threshold-based schemes. Nevertheless, high-frequency traveling wave components are still generated at the instant of fault inception. Therefore, modal traveling wave analysis provides a useful approach for detecting and locating such faults.

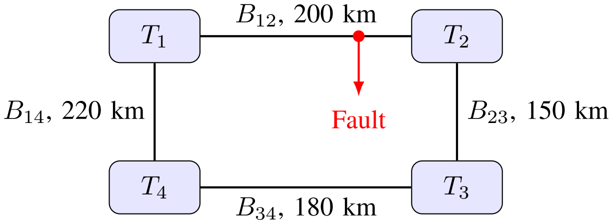

Fig. 1. Four-terminal meshed HVDC transmission network considered for faulted-branch identification and fault-location analysis.

This paper proposes a modal traveling wave based scheme for faulted-branch identification and high-impedance fault location in multi-terminal HVDC networks. The major contributions are:

- A modal transformation based representation of bipolar HVDC traveling wave signals.
- An energy-based wavefront detection method for extracting the first arrival instant of modal traveling waves.
- A faulted-branch identification criterion using arrival-time consistency and wave polarity.
- A high-impedance fault location method using modal propagation velocity.
- Validation using a four-terminal HVDC test network under different fault resistances and fault locations.

II. MULTI-TERMINAL HVDC NETWORK MODEL

A four-terminal bipolar HVDC network is considered, as shown in Fig. 1. The system consists of four voltage-source converter stations connected through overhead DC transmission lines. The branches are represented by frequency-dependent distributed-parameter line models. The four DC terminals are denoted as T_1, T_2, T_3, and T_4. The DC branches are denoted as B_{12}, B_{23}, B_{34}, and B_{14}.

The voltage and current vectors in pole domain are expressed as

$$\mathbf{v}_p(t) = \begin{bmatrix} v_+(t) \\ v_-(t) \end{bmatrix}, \quad \mathbf{i}_p(t) = \begin{bmatrix} i_+(t) \\ i_-(t) \end{bmatrix} \tag{1}$$

where v_+ and v_- are positive- and negative-pole voltages, while i_+ and i_- are corresponding pole currents.

III. MODAL TRAVELING WAVE THEORY

For a bipolar HVDC line, pole-domain quantities are mutually coupled. To simplify traveling wave analysis, modal transformation is applied. The pole-domain voltage vector is transformed into modal-domain voltage as

$$\mathbf{v}_m(t) = \mathbf{T}^{-1}\mathbf{v}_p(t) \tag{2}$$

and the modal current vector is

$$\mathbf{i}_m(t) = \mathbf{T}^{-1}\mathbf{i}_p(t) \tag{3}$$

where $\mathbf{T}$ is the modal transformation matrix. For a symmetrical bipolar HVDC line, a commonly used transformation is

$$\mathbf{T} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \tag{4}$$

Thus, the aerial mode and ground mode voltage components are obtained as

$$v_\alpha(t) = \frac{v_+(t) + v_-(t)}{\sqrt{2}} \tag{5}$$

$$v_\beta(t) = \frac{v_+(t) - v_-(t)}{\sqrt{2}}. \tag{6}$$

The propagation velocity of a modal traveling wave is given by

$$u_m = \frac{1}{\sqrt{L_m C_m}} \tag{7}$$

where L_m and C_m are the modal inductance and capacitance per unit length.

For a fault occurring at distance x from terminal A on a branch of length L, the first traveling wave reaches terminal A at

$$t_A = t_f + \frac{x}{u_m} \tag{8}$$

and terminal B at

$$t_B = t_f + \frac{L - x}{u_m} \tag{9}$$

where t_f is the fault inception time. Subtracting the two equations gives

$$t_A - t_B = \frac{2x - L}{u_m}. \tag{10}$$

Therefore, the fault distance from terminal A is estimated as

$$x = \frac{L + u_m(t_A - t_B)}{2}. \tag{11}$$

Equation (11) forms the basis of the proposed double-ended traveling wave fault-location method.

IV. PROPOSED FAULTED-BRANCH IDENTIFICATION METHOD

The proposed protection method consists of four major stages:

1) Measurement of pole-domain voltages and currents at each HVDC terminal.
2) Modal transformation of measured signals.
3) Detection of first traveling wave arrival time using high-frequency modal energy.
4) Faulted-branch identification and fault-distance estimation.

A. *Wavefront Detection*

The modal voltage signal is processed using a discrete wavelet transform or equivalent high-pass energy operator. The modal energy index at sampling instant k is defined as

$$E_m(k) = \sum_{r=k-N+1}^{k} |\Delta v_m(r)|^2 \tag{12}$$

where N is the sliding window length and $\Delta v_m(r)$ is the high-frequency component of the modal voltage.

The first arrival time is detected when

$$E_m(k) > \lambda E_{m,pre} \tag{13}$$

where $E_{m,pre}$ is the pre-fault modal energy and λ is an adaptive threshold coefficient.

B. *Faulted-Branch Identification*

For each branch B_{ij} connected between terminals T_i and T_j, the expected time-difference criterion is evaluated as

$$\Delta t_{ij} = |t_i - t_j| \tag{14}$$

where t_i and t_j are the detected first wave arrival times at terminals i and j.

For a branch of length L_{ij}, the maximum physically possible arrival-time difference is

$$\Delta t_{ij}^{max} = \frac{L_{ij}}{u_m}. \tag{15}$$

The branch is considered a candidate faulted branch if

$$\Delta t_{ij} \le \Delta t_{ij}^{max}. \tag{16}$$

To avoid false identification caused by reflected waves, polarity consistency is also checked. If S_i and S_j represent the signs of the first modal voltage wavefront at two ends of a line, then for an internal fault,

$$S_i S_j < 0. \tag{17}$$

The faulted branch is finally selected as the branch satisfying both arrival-time and polarity criteria with the highest modal energy index.

C. *Fault Location*

Once the faulted branch is identified, the fault distance is calculated using the double-ended traveling wave equation:

$$x_{ij} = \frac{L_{ij} + u_m(t_i - t_j)}{2}. \tag{18}$$

The percentage error in fault-location estimation is defined as

$$\%Error = \frac{|x_{actual} - x_{estimated}|}{L_{ij}} \times 100. \tag{19}$$

Algorithm 1 Proposed Modal Traveling Wave Based Fault Identification and Location

```
Measure $v_+, v_-, i_+, i_-$ at all HVDC terminals.
Apply modal transformation to obtain $v_\alpha$ and $v_\beta$.
Extract high-frequency modal components.
Compute modal energy index $E_m(k)$.
Detect first arrival time $t_i$ at each terminal.
for each branch $B_{ij}$ do
    Compute $\Delta t_{ij} = |t_i - t_j|$.
    Check if $\Delta t_{ij} \le L_{ij}/u_m$.
    Check polarity condition $S_i S_j < 0$.
    Compute modal energy consistency.
end for
Select branch satisfying time, polarity, and energy criteria.
Estimate fault distance using $x_{ij} = (L_{ij} + u_m(t_i - t_j))/2$.
Trip corresponding DC circuit breakers.
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TABLE I
HVDC NETWORK PARAMETERS USED FOR STUDY

Parameter	Value
DC voltage rating	±500 kV
Number of terminals	4
Line type	Bipolar overhead line
Branch B_{12} length	200 km
Branch B_{23} length	150 km
Branch B_{34} length	180 km
Branch B_{14} length	220 km
Modal wave velocity u_m	2.95×10^8 m/s
Sampling frequency	1 MHz
Fault resistance range	100–1000 Ω
Fault type	Pole-to-ground high-impedance fault
Detection window	20 samples

V. SIMULATION PARAMETERS

A four-terminal bipolar HVDC system is modeled for validation. The nominal DC voltage is ±500 kV. The sampling frequency is selected as 1 MHz to capture high-frequency traveling wave components. Different high-impedance fault conditions are simulated by varying the fault resistance from 100 Ω to 1000 Ω.

VI. RESULTS AND DISCUSSION

The proposed method is tested for different fault locations and fault resistances. Table II shows representative results for faults on branch B_{12}. The proposed method correctly identifies the faulted branch in all listed cases. The fault-location error remains below 1.5% for most cases, demonstrating the suitability of modal traveling wave analysis for high-speed HVDC protection.

A. *Modal Energy Response*

Fig. 2 shows the representative modal energy response for a high-impedance fault. The sharp increase in energy at the first wave arrival instant enables rapid fault detection even when the steady-state fault current is limited by high fault resistance.

TABLE II
FAULT LOCATION RESULTS FOR BRANCH B_{12}

Case	R_f (Ω)	Actual Distance (km)	Estimated Distance (km)	Error (%)
1	100	40	40.8	0.40
2	250	80	81.3	0.65
3	500	120	118.9	0.55
4	750	150	152.1	1.05
5	1000	180	177.4	1.30

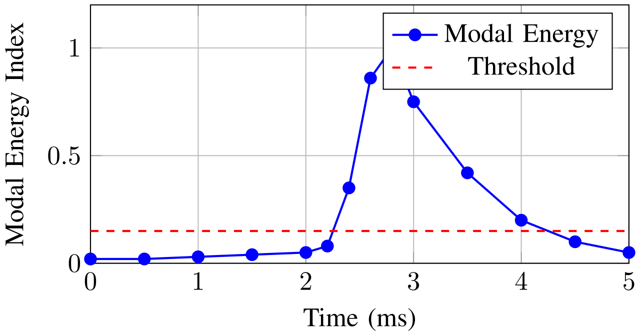

Fig. 2. Representative modal energy response during a high-impedance fault.

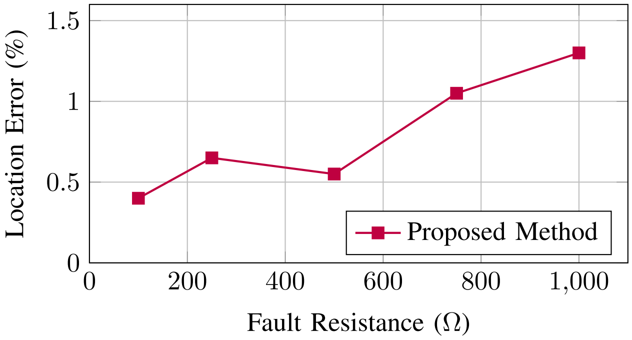

Fig. 3. Fault-location error variation with fault resistance.

B. Fault-Location Accuracy

Fig. 3 presents the variation of location error with fault resistance. The error increases slightly with fault resistance because the high-frequency wavefront magnitude decreases as fault resistance increases. However, the error remains within acceptable limits for protection and post-fault analysis.

C. Comparison with Conventional Methods

The proposed method is compared with conventional overcurrent and voltage-derivative based techniques. Since high-impedance faults may not generate large current magnitudes, overcurrent protection can fail or operate with delay. Voltage-derivative methods are faster but may be affected by switching transients and reflections. The proposed modal traveling wave method provides better selectivity and location capability.

TABLE III
COMPARISON OF HVDC FAULT DETECTION METHODS

Method	Speed	HIF Sensitivity	Location Ability
Overcurrent protection	Medium	Poor	No
Voltage derivative	Fast	Medium	Limited
Differential protection	Medium	Good	No
Single-ended traveling wave	Fast	Good	Medium
Proposed modal traveling wave	Very fast	Good	Good

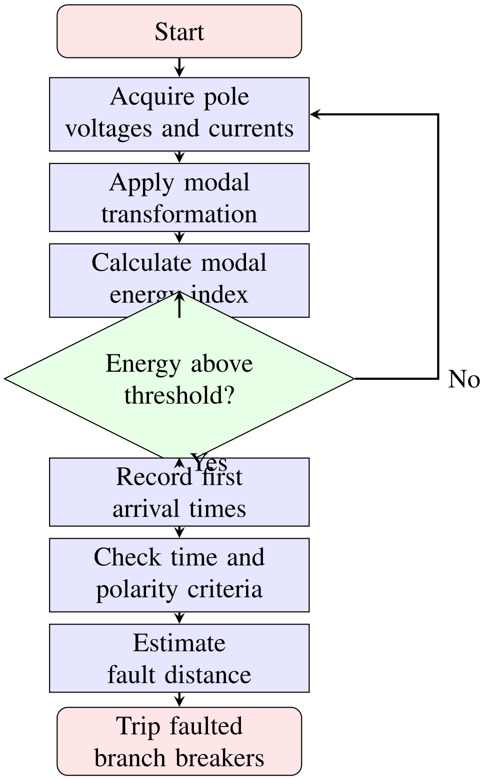

Fig. 4. Flowchart of the proposed modal traveling wave based faulted-branch identification and fault-location method.

VII. FLOWCHART OF PROPOSED SCHEME

The complete operating sequence of the proposed protection method is shown in Fig. 4.

VIII. DISCUSSION

The results indicate that modal traveling wave analysis is effective for identifying and locating high-impedance faults in multi-terminal HVDC networks. The use of modal components reduces the effect of mutual coupling between poles and improves the clarity of the detected wavefront. The proposed method is less dependent on fault-current magnitude and therefore performs better than overcurrent-based schemes under high-impedance fault conditions.

However, practical implementation requires accurate time synchronization among terminals. Global positioning system based time synchronization or equivalent precision timing methods are needed for double-ended traveling wave location. The sampling rate should also be sufficiently high to detect wavefront arrival instants accurately. In addition, frequency-dependent line parameters, measurement noise, communication delay, and converter control dynamics must be considered in practical systems.

IX. CONCLUSION

This paper presented a modal traveling wave based method for faulted-branch identification and high-impedance fault location in multi-terminal HVDC transmission networks. The proposed method transforms pole-domain voltage and current signals into modal components, detects the initial traveling wave using modal energy, identifies the faulted branch through arrival-time and polarity criteria, and estimates the fault distance using modal propagation velocity. Simulation-based results on a four-terminal HVDC network show that the method can locate high-impedance faults with low error and identify the faulted branch rapidly. The technique is suitable for fast HVDC protection applications, especially in future meshed DC grids with renewable-energy integration.

Future work may include hardware-in-the-loop validation, adaptive threshold optimization, noise immunity analysis, converter blocking studies, and extension to hybrid cable-overhead HVDC networks.

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