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Traveling-wave based fault location estimation in FACTS compensated transmission system: Recent status, challenges and future research directions

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REVIEW HIGHLIGHTS

- Recent state-of-art of traveling-wave based fault location techniques for FACTS compensated system is presented highlighting future research directions.
- Importance of fault location techniques and their classification are discussed.
- Overview of traveling-wave based fault location technique and effects of FACTS devices on system are presented.

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Traveling-wave based fault location estimation

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ABSTRACT

This article presents a recent literature review on traveling wave-based fault location estimation in flexible alternating current transmission system (FACTS) compensated transmission system. The review aims to provide an overview of the current state-of-the-art in traveling wave-based fault location methods and their applications in FACTS compensated power systems. Firstly, the importance of fault location techniques and their classification are discussed. Secondly, the basic theory behind traveling-wave based fault location methods is presented. Further, the effects of presence of different FACTS devices are presented to highlight the challenges in developing efficient fault location methods for FACTS compensated transmission system. The survey covers reported traveling-wave based fault location techniques and highlights the current status and challenges. Additionally, the survey reviews recent advancements in the field and identifies future research directions. The study concludes by summarizing the main findings and providing recommendations for further research. The presented literature review provides valuable insights for researchers, engineers, and practitioners in the field of power system protection and control.

Specifications table

Subject area:	Engineering
More specific subject area:	*Power system protection and control*
Name of the reviewed methodology:	*Traveling-wave based fault location estimation*
Keywords:	*Traveling-wave, fault location, FACTS devices, signal decomposition techniques, transmission lines*
Resource availability:	*N.A.*
Review question:	1. How fault location methods for transmission lines are important for secure and reliable operation of modern power systems? 2. What is broad classification of fault location methods? 3. How FACTS devices affect fault location methods? 4. What are limitations of traveling-wave methods?

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Method details

Introduction

The ever-increasing power demand is pushing electric utility to increase power generation. The generation is either increased by capacity expansion or renewable energy integration. However, capacity expansion is not always environmentally and economically feasible. Further, the penetration level of renewable energy in conventional system is still minimal but steadily growing. Moreover, there is one solution to above problems is to enhance the power transfer capability of existing lines thereby minimizing the losses. Presently, the aforementioned solution is practically possible with the aid of flexible alternating current transmission system (FACTS) technology. FACTS devices enhance the power transfer capability of lines to their maximum limit and minimize the losses [1].

Further, the complex structure of power system makes it prone to unwanted operating events like line faults, loss of generation, failure of protection coordination etc. During these operating conditions, the security and reliability of power networks are needed to be ensured. Power system restoration is an important aspect of power system which helps in restoring the original system after occurrence of transient conditions like line faults. For quick restoration of lines experiencing faults, accurate fault location is necessary. In literature, several fault location methods (FLMs) are reported for conventional system [2]. In FACTS compensated system, there are variations in measured voltage and current signals and these variations may affect the performance of FLMs. However, there are limited reports which explore the development of FLM for FACTS compensated system [3].

The work presented here explores the recent available reports in context of traveling-wave based fault location estimation in FACTS compensated system. The flow-diagram of FLM is illustrated in Fig. 1. FLMs can be broadly classified into impedance-based methods, artificial-intelligence methods and traveling-wave methods [4]. From the figure, it can be seen that FLMs is further categorized on the basis of input signals utilized by FLM for estimation of fault location. The input data can be two-terminal data of a line or information from only one end of the line. The type of input signals can be either voltage or current signals or both of them. The reported FLMs are applied to the system with different structure. Each type of broadly classified FLM possesses different characteristics which are listed in Table 1. From the table it can be observed that traveling-wave methods are very fast compared to others but it is not much economical than others since installation cost is high. Further, it is noted that impedance-based methods can be easily implemented practically in comparison to other FLMs. One of the major requirements for efficient development of FLM is the choice of sampling frequency at which measured signals are sampled. Traveling-wave methods require high sampling frequency for accurate estimation of fault location compared to other FLMs. But, presently this fact does not constitute a disadvantage for traveling-wave methods since the signals now can be sampled easily at high sampling frequency (> 1 MHz) [5].

Presently, traveling-wave based fault locators are practically available since high sampling frequency is now possible [6]. Additionally, the efficiency of conventional and recently developed FLMs are required to be examined for FACTS compensated transmission system. From the number of reports available in literature, it can be concluded that there are very limited reports available in literature in context of development of FLMs for FACTS compensated system. Additionally, there is no report available in literature which specifically presents a review of report regarding FLMs developed for FACTS employed transmission system utilizing concept

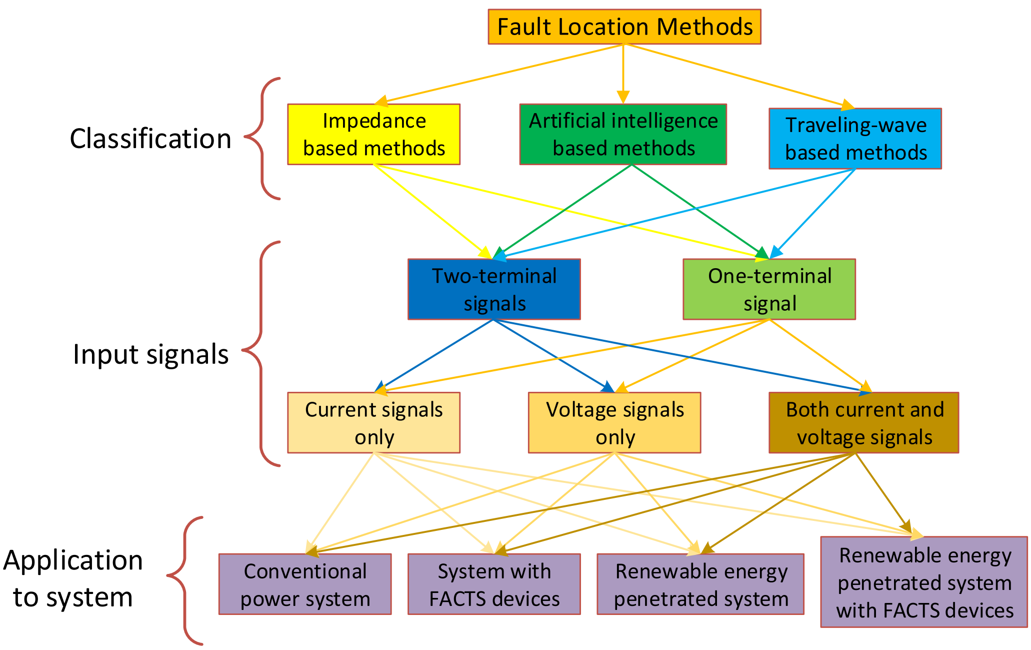

Fig. 1. Flow-diagram of FLM.

Table 1
Characteristics of FLMs.

Type of FLM	Speed of operation	Installation cost	Practical feasibility	Sampling frequency
Impedance-based methods	medium	low	high	low
Artificial intelligence-based methods	fast	low	medium	low
Traveling-wave based methods	Very fast	high	medium	high

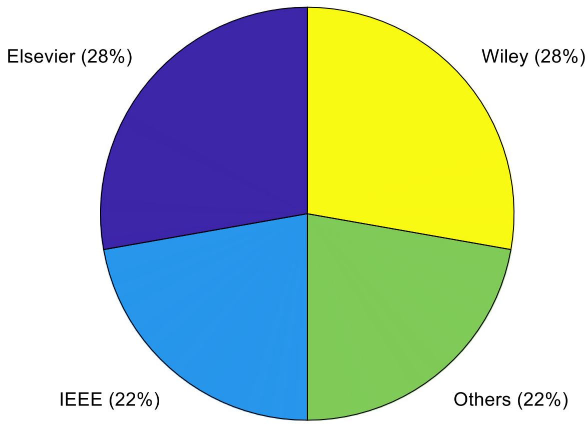

Fig. 2. Pie-chart of reports published with different publishers.

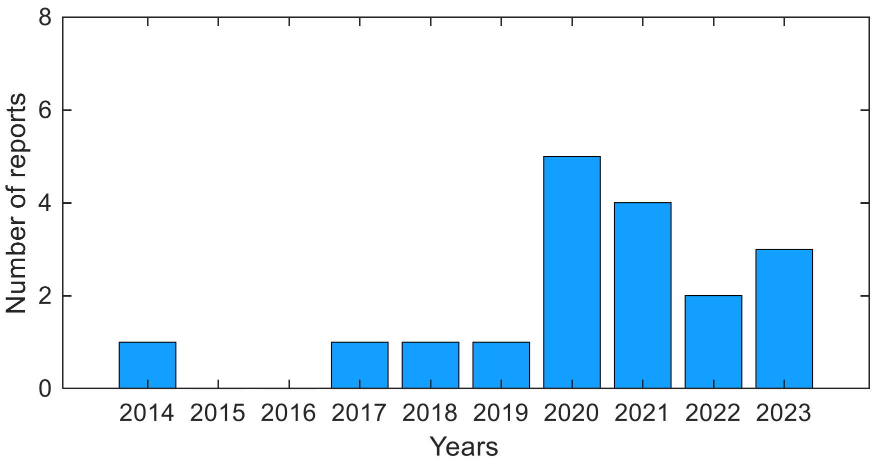

Fig. 3. Bar-chart of reports published in different years.

of traveling waves. In this context, a comprehensive literature survey on the use of traveling wave-based fault location in FACTS compensated power systems is highly desirable and the same is presented in this work. The objective of this survey is to provide a comprehensive overview of the current state-of-the-art in traveling wave-based fault location methods and their applications in FACTS compensated power systems. Additionally, the survey reviews recent advancements in the field and identifies future research directions. The study concludes by summarizing the main findings and providing recommendations for further research.

For review, several reports published by different publication houses from year 2014 to 2023 are considered. The pie-chart of publishers documenting reports on development of traveling wave-based FLMs for FACTS compensated system is depicted in Fig. 2. From the figure, it can be seen that most of the reports are published by Wiley and Elsevier publishing houses. Further, a bar-chart is shown in Fig. 3 showing the number of reports available in particular years from 2014 onward. From the chart, it can be noticed that in recent years (2020 onward) more research is carried out on development of FLMs based on traveling waves for FACTS compensated system. From this fact, it can be concluded that more attention is required to this area of research.

Overview of traveling-wave based FLM

Whenever a transmission line experiences a fault, traveling-waves emanated at the fault point and travels along the line to get terminated at the bus terminals. The information of time of arrival traveling-wave at terminals is used in determining the location

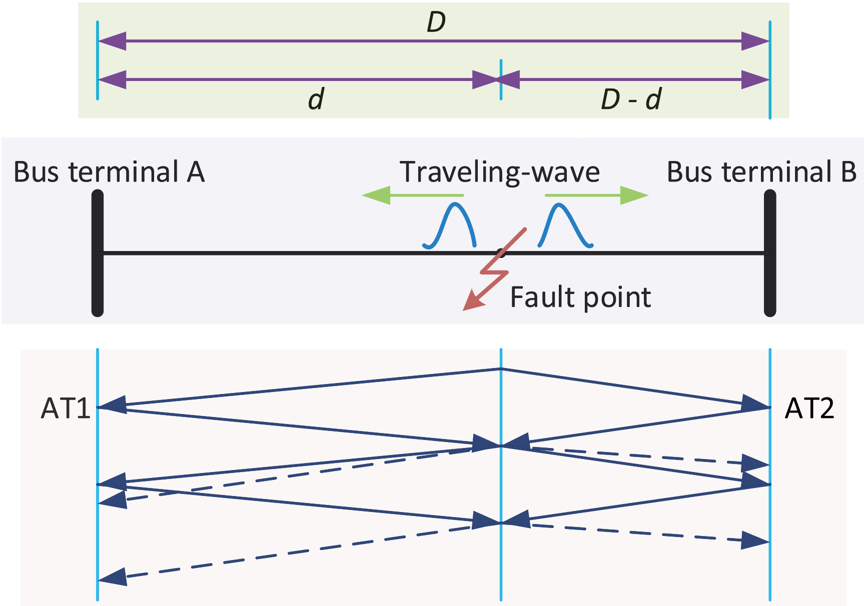

Fig. 4. Sample transmission line.

of the faults. Fig. 4 shows transmission line AB of total length *D*. The fault point is located at a distance of *d* from bus A. When fault occurs, traveling-waves emanate from fault point and travel towards bus terminals. AT1 and AT2 are time of first arrival waves at bus terminals A and B, respectively. Solid and dotted arrows of traveling-waves represent reflected and refracted waves, respectively.

Depending on the one-terminal or two-terminal information of arrival time of traveling wave (ATTW), the traveling wave is classified as single-ended or double-ended FLM. Let, υ is the traveling-wave speed in km/s and total line length *D* and fault distance *d* are in km. The estimated fault location, *EFL* for double-ended FLM is represented as

$$EFL = \frac{D - \upsilon(\mathrm{AT2} - \mathrm{AT1})}{2} \tag{1}$$

The corresponding percentage error *E* is calculated as

$$E = \frac{|EFL - d|}{D} \times 100 \tag{2}$$

As it can be seen in Fig. 4, the traveling wave emanates from fault point and travels towards bus terminals. After reaching the terminals, it is reflected back and move towards fault point. At fault point, some part of wave is refracted and move fromward (shown by dotted arrow) and rest part of the wave again is reflected and travels towards bus terminals. This process continues till the energy of the waves diminishes in the lien. For single-ended FLM, two consecutive ATTW at one terminal is used for fault location. Let, the total sweep-time by arrival-wave between terminals A and B is Δt, then estimated fault location *EFL* is calculated by

$$EFL = \frac{\upsilon \times \Delta t}{2} \tag{3}$$

The percentage error in this case is given by Eq. (2).

Effects of FACTS devices

Incorporation of FACTS devices in the transmission system affects the measured voltage and currents signals. The variations introduced by FACTS devices are more prominent in transient conditions like transmission line faults. Series FACTS devices alter the transmission line reactance and thus, introduces variations in measured signals. Shunt FACTS devices inject current to the connected bus to maintain flat voltage level and thus may vary the measured signals. Further, series-shunt FACTS devices comparatively affect the signals significantly than other FACTS devices. Fig. 5 shows the effects of a 100 MVA series-shunt FACTS device i.e., unified power flow controller (UPFC) on 500 kV transmission system. The fault is initiated at 0.2 s and the variations in current, voltage, active and reactive power in presence of UPFC is compared with measured signals without UPFC in the same system. Fig. 5(a) shows instantaneous current of phase ‘A’. it can easily be observed that in presence of UPFC the magnitude of current signals increases after inception of fault. Similarly, the instantaneous voltage signals of phase ‘A’ is shown in Fig. 5(b). From the figure, it can be seen that variations are introduced in the signal in presence of UPFC. However, this variation is not much significant. Fig. 5(c) and (d) depict the active and reactive power flow through the transmission line, respectively. A clear variation in the power signals can be observed in presence of UPFC. Therefore, it is concluded that the presence of UPFC introduces variations in measured signals. The similar fact

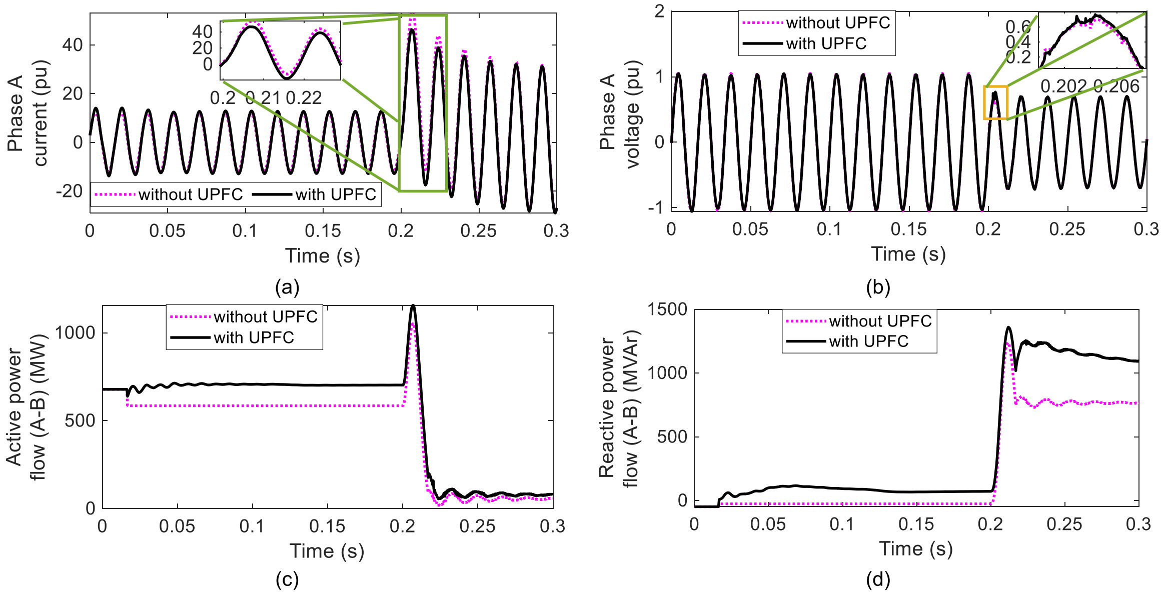

Fig. 5. Effects of UPFC on system. (a) Current signal. (b) Voltage signal. (c) Active power flow. (d) Reactive power flow.

is true with series and shunt FACTS devices. Consequently, it is required to investigate the performance of existing FLMs for FACTS compensated system and develop novel FLMs.

Traveling-wave based FLM for series FACTS compensated system

Several reports are available in literature regarding development of traveling-wave based FLM for series FACTS compensated system. In general, static synchronous series compensator (SSSC) and thyristor-controlled series compensator (TCSC) are two popular series FACTS device used for providing series compensation to the system. The literature survey will be carried out for mentioned FACTS compensated system.

In [7], a two-terminal traveling-wave based FLM is developed for series FACTS compensated transmission system connected to wind farms. Estimation of signal parameters via rotational invariance technique (ESPRIT) is used to detect ATTW at bus terminals. Instantaneous voltage signals are transformed to obtain modal signals and aerial-mode signals are used as input signals. IEEE-14 bus test system is modified by replacing generator at bus 1 with a wind farm of same rating. Fixed series capacitor (FSC) and TCSC are used for providing series compensation. A compensation level of 40% is considered. The peak of the squared error signal (the difference between original aerial mode signal and reconstructed signal via ESPRIT) is used to determine ATTW at the terminals which is further utilized to estimate the fault location. The developed FLM is examined under different operating conditions of varying faults, distances, fault resistances, location of TCSC installation point and noise in the signals. The proposed FLM is found to be performing efficiently.

In [8], discrete wavelet transform (DWT) and probabilistic neural network (PNN) are used for fault location in TCSC compensated system. Single-ended voltage measurements are used as input signals. TCSC is providing series compensation to the system. A sampling frequency of 100 kHz is considered and the results for fault location are acceptable since the percentage errors are found to be less than 1%. The performance of proposed FLM is investigated for the system with varying fault types and resistances. Further, load angle and fault resistance variations are further considered for examining the efficient performance of presented FLM. The prosed algorithm is found to be reliable in locating and classifying faults. The impacts of harmonic frequencies generated by TCSC is additionally considered to validate the efficient performance of proposed FLM.

In [9], a single-ended FLM is proposed for TCSC compensated system. Voltage signals is used as input signals. Mathematical morphology filter (MMF) and DWT are used as signal processing tools. The sampling frequency of 1 MHz is considered. Several test scenarios of varying system parameters are considered to test the performance of the system. Basically, all possible types of faults are initiated at the middle of line with different inception angles and the performance of proposed FLM is validated.

In [10]. Fast discrete S-transform (FDST) is used for fault location in TCSC transmission system connected to wind farms. Currents signals measured at each terminal are used to obtain modal signals. These modal signals are then decomposed using FDST to extract information of traveling wave. Arrival time of the wave is estimated from the first peak of the modal signal. Fault location is calculated using estimated arrival time of traveling waves. A sampling frequency of 200 kHz is considered. For simulation, a 200 km, 400 kV transmission system with TCSC compensation is used. The performance of proposed FLM is investigated for TCSC dynamics and wind variations. System parameters are additionally varied to test the robustness of the FLM.

Table 2
FLMs for series FACTS compensated system.

Method	Input data	Input signal	Technique	Compensation	Sampling frequency (kHz)	System
Ref. [7]	Two-terminal	Voltage	ESPRIT	FSC, TCSC, Wind farms	1000	Modified IEEE-14 bus test system
Ref. [8]	Single-ended	Voltage	DWT, PNN	TCSC	100	4-machine system
Ref. [9]	Single-ended	Voltage	MMF, DWT	TCSC	1000	4-machine system
Ref. [10]	Two-terminal	Current	FDST	TCSC, Wind farms	200	200 km, 400 kV transmission system
Ref. [11]	Two-terminal	Voltage	DWT	TCSC	100	4-machine system
Ref. [12]	Single-ended	Current and voltage	FFT	TCSC	–	50-Hz, 380-kV overhead transmission line of length 600 km
Ref. [13]	Two-terminal	Current and voltage	Traveling wave	TCSC	1000	Korean grid

In [11], DWT assisted traveling-wave based FLM is proposed for TCSC compensated system. Voltage signals measured at terminals are used as input signals. The signals are sample at rate of 100 kHz. A 4-machine system with TCSC system is considered. Several parameters are varied to test the performance of the proposed FLM. The proposed FLM is found to be location all eleven types of faults. The impacts of TCSC on the directionality is explored in this study. The maximum percentage error is found to be 1.25%.

In [12], fast-Fourier transform (FFT) is applied to obtain frequency domain conversion of transient current and voltage signals. The frequency spectrum thus obtained is utilized in determination of fault location by analyzing the frequencies of fault generated harmonics. TCSC with different compensation level is considered to validate the performance of the proposed method. While applying, the source induction effect is eliminated and estimation accuracy is improved by introducing a waveform relaxation method. The method is found to be performing effectively in locating faults for different compensation levels under consideration of varying fault resistance and phase angle.

In [13], a traveling wave approach is adopted to locate faults in Korean grid where 345 kV line is compensated with TCSC. The performance of the proposed method is validated by varying fault distances from 0 to 100%. Shinjecheon-Donghae line and Shinyoungju-Hanul line are used for initiation of the faults. Analysis of the results shows that an error in distance varies from 0.1 to 0.32%.

A summary of important aspects of FLMs for series FACTS compensated system is presented in Table 2. From the table, it can be noticed that both two-terminal and single-ended FLMs are developed. Mostly, voltage signals are chosen as input signals. The prime reason may be the transient features are more pronounced in current signals. A high sampling frequency is used in most of reports and it is obvious since the accuracy of traveling wave methods increases with increase in sampling frequency. The performance of most of reported FLMs are simulated on small test system.

As mentioned in Table 2, ESPRIT is used to decompose modal voltage signals [7]. The difference of original modal voltage signal and reconstructed signal is regarded as error signal. From the peak of the squared error signal, ATTW is estimated. A case study to depict the same is considered here as explained in [7]. A three-phase to ground fault is initiated at 0.6 s at a fault distance of 150 km. The sampling frequency is 1000 kHz. The line length is 200 km and wave speed is equal to 2.8994e5 km/s. Fig. 6 depicts the working ESPRIT based FLM for the mentioned test case. Fig. 6(a) shows the original aerial-mode signal and reconstructed signal via ESPRIT for bus B1. The squared error signal is shown in Fig. 6(b). From this figure, ATTW is estimated from the peak and found to be 0.60052167 s. Similarly, for bus 2, ATTW is estimated from Fig. 6(d) and it is found to be equal to 0.600175 s. Using estimated ATTWs, estimated fault location *EFL* and corresponding percentage error *E* are calculated as follows:

$$EFL = \frac{200 - (2.8994e5(0.600175 - 0.60052167)}{2} = 150.25675\ \text{km} \tag{4}$$

$$E = \frac{|150.25675 - 150|}{200} \times 100 = 0.1284 \tag{5}$$

The percentage error is found to be 0.1284 which is well within acceptable limit of 1%.

Traveling-wave based FLM for shunt FACTS compensated system

In [14], a game theory and DWT approaches are adopted for fault location in static synchronous compensator (STACOM) incorporated system. Sigle-ended voltage signals are used for decomposition using game theory and DWT approaches. A sampling frequency of 100 kHz is used for locating faults whereas a sampling frequency of 1 MHz is considered for comparing its results with existing techniques. Different test scenarios are considered to examine the efficient performance of the proposed FLM. System parameters like different fault distances and inception angles are varied for all possible types of faults.

In [15], a game theory approach is proposed for locating faults in static var compensator (SVC) employed transmission system. A single-ended voltage signals is utilized as input signals. MMF and DWT is used to decompose the signals. A sampling frequency of 1 MHz is considered for simulation. 4-machine test system with SVC compensation is simulated. Systems parameters and fault parameters are varied to test the efficient performance of the proposed method. The impacts of switching of SVC on protection schemes are studied in this work. Proposed FLM is found to be efficient in locating faults and possessing noise immunity.

In [16], traveling-wave based FLM is proposed for STATCOM compensated system. Here, single-end voltage measurements are used as input signals. The signals are decomposed using DWT. A sampling frequency of 200 kHz is used for simulation. A 4-machine system

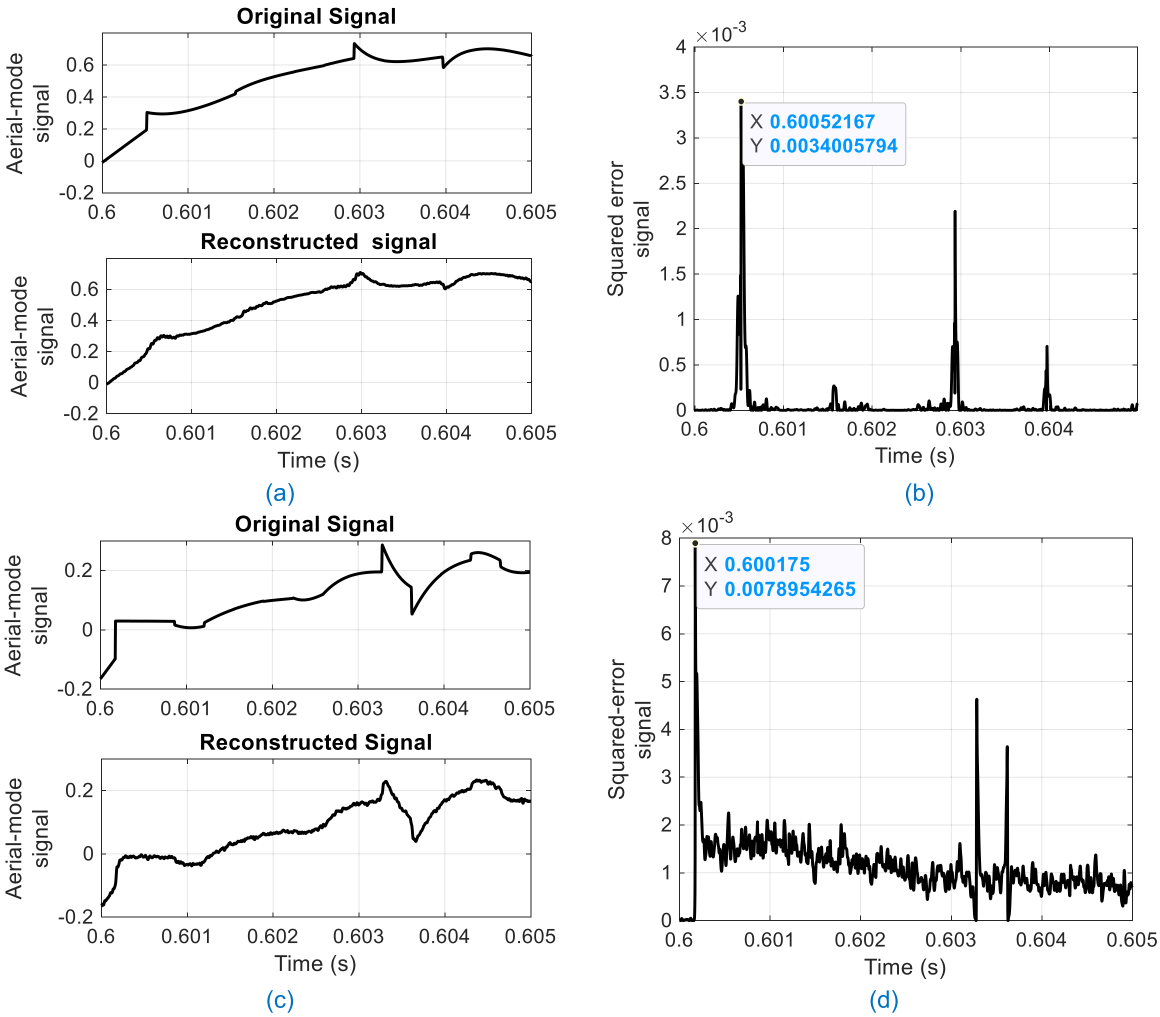

Fig. 6. ESPRIT based FLM for TCSC compensated system. (a) Original and reconstructed (via ESPRIT) aerial-mode signals of bus B1. (b) Squared error signal of bus B1. (c) Original and reconstructed (via ESPRIT) aerial-mode signals of bus B2. (d) Squared error signal of bus B2.

with double-circuit line compensated with STATCOM is utilized. Different test cases are considered to evaluate the performance of proposed FLM. It is found that the presence of STATCOM or change in its operating modes does not affect the performance of proposed FLM. High accuracy is achieved in fault location estimation.

In [17], a dual-time transform (DTT) is sued to develop a fault location estimation algorithm for STATCOM compensated system connected to wind farms. Single-needed current signals are decomposed by DTT. The aerial-mode signals are obtained from current signals via modal transformation. These modal signals are utilized in estimation of fault location. DTT is utilized for decomposition of current signals with a sampling frequency of 10 kHz. A two-bus power system with STATCOM is used for simulation. Real-time validation of the proposed method is carried with Opal-RT software. Comparative study is carried out and it is found the performance of proposed FLM is efficient.

In [18], variational mode decomposition (VMD) and Teager energy operator (TEO) are used to develop a FLM for STATCOM compensated transmission system. A 500 kV transmission system with 100 MVA STATCOM is used for simulation. Instantaneous voltage signals are transformed via modal transformation. Aerial-mode voltage signals are decomposed using VMD and energy is obtained for decomposed signals via TEO. A sampling frequency of 600 kHz is considered. Different test scenarios of varying system and fault parameters are considered to test the performance of the proposed FLM. The presented FLM is found to be efficient and percentage error is within acceptable limit of 1%.

In [19], short-time matrix pencil method (STMPM) is used to determine the fault location in STATCOM compensated system. STMPM is used to derive the time-indexed complex frequencies and finally damping factors are obtained. Linear regression is performed on obtained damping factors and from the zero-crossing point, the arrival time of traveling wave is estimated. Further, the information of time of arrival waves, fault location is obtained. The efficacy of proposed method is validated for the system operating

Table 3
FLMs for shunt FACTS compensated system.

Method	Input data	Input signal	Technique	Compensation	Sampling frequency (kHz)	System
Ref. [14]	Single-ended	Voltage	Game theory, DWT	STATCOM	100, 1000	4-machine system
Ref. [15]	Single-ended	Voltage	Game theory, DWT, MMF	SVC	1000	4-machine system
Ref. [16]	Single-ended	Current	DWT	STATCOM	200	4-machine system, double-circuit line
Ref. [17]	Single-ended	Current	DTT	STATCOM, wind-farm	10	2-bus test system
Ref. [18]	Two-terminal	Voltage	VMD, TEO	STATCOM	600	500 kV transmission system
Ref. [19]	Two-terminal	Voltage	STMPM	STATCOM	600	500 kV transmission system

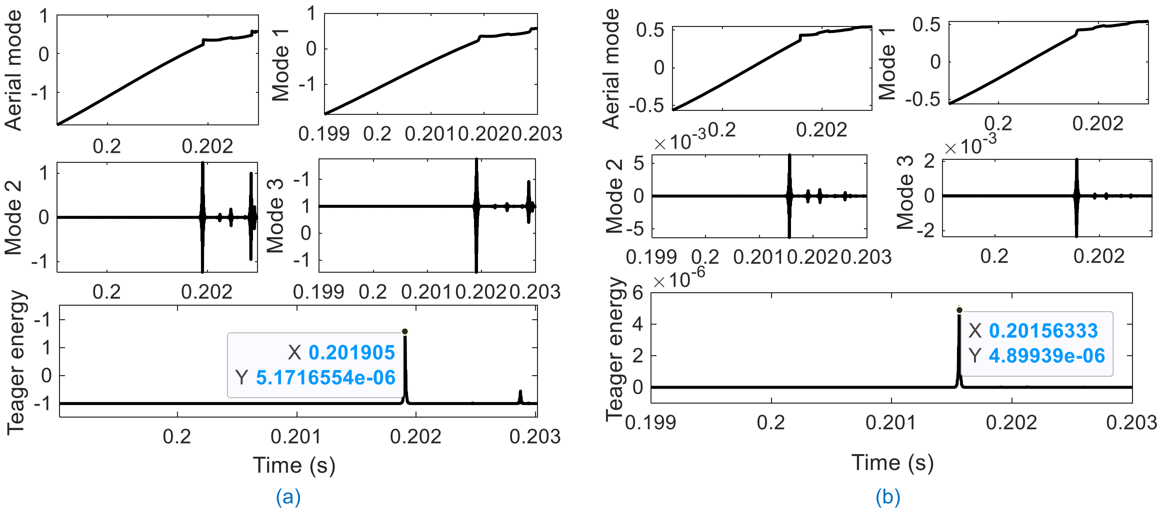

Fig. 7. TEO assisted VMD-based FLM for STATCOM compensated system. (a) ATTW estimation for bus B1. (b) ATTW estimation for bus B2.

under varying fault distances, types, fault resistances, inception angles and sampling frequency. Real-time validation of the proposed method is carried out to ascertain its performance.

A summary of significant points of FLMs for shunt FACTS compensated system is presented in Table 3. From the table, it can be observed that mostly single-ended FLMs are developed for shunt FACTS compensated system. Voltage signals are more preferred over current signals as input signals. The least prominence of transient features in voltage signals may be the reason behind its selection. A high sampling frequency is used in most of cases in order to achieve higher accuracy for FLMs. Small test system is used to validate the performance of reported FLMs.

As mentioned in Table 3, VMD and TEO are used to decompose modal voltage signals [18]. The modal voltage signals are decomposed using VMD up to three level and TEO is applied on mode 3 signal to obtain energy signal. From the peak of energy signal, ATTW is estimated. A case study to illustrate the same is considered here as explained in [18]. A three-phase to ground fault is initiated at 0.2 s at a fault distance of 150 km. The sampling frequency is 600 kHz. The line length is 200 km and wave speed is equal to 2.8994e5 km/s. Fig. 7 illustrates the working TEO assisted VMD based FLM for the mentioned test case. Fig. 7(a) shows the decomposition of aerial-mode voltage signal to mode 3 signal via VMD and energy signal is obtained after applying TEO on mode 3 signal for bus B1. From this figure, ATTW is estimated from the peak of the energy signal and is found to be 0.201905s. Similarly, for bus 2, ATTW is estimated from Fig. 7(b) and it is found to be equal to 0.20156333s. Using estimated ATTWs, estimated fault location *EFL* and corresponding percentage error *E* are calculated as follows:

$$EFL = \frac{200 - (2.8994e5(0.20156333 - 0.201905)}{2} = 150.0147 \text{ km} \tag{6}$$

$$E = \frac{|150.0147 - 150|}{200} \times 100 = 0.0073 \tag{7}$$

The percentage error is found to be 0.0073 which is well within acceptable limit of 1%.

Traveling-wave based FLM for series-shunt FACTS compensated system

In [20], fast-discrete orthogonal S-transform (FDOST) is used to propose a FLM for UPFC compensated system. Single-ended voltage signal is used as input signal. FDOST decomposes these signals to extract the information of ATTW. Principle component analysis is performed to obtain feature vectors and Gaussian process regression is applied to obtain fault location. A sampling frequency of 100 kHz is considered. For simulation, a 500 kV transmission system of 300 km line length is utilized. Several test scenarios of system

Table 4
FLMs for series-shunt FACTS compensated system.

Method	Input data	Input signal	Technique	Compensation	Sampling frequency (kHz)	System
Ref. [20]	Single-ended	Voltage	FDOST	UPFC	100	500 kV transmission line of 300 km length
Ref. [3]	Two-terminal	Voltage	ITD	UPFC	600	500 kV transmission system with 100 MVA UPFC
Ref. [21]	Two-terminal	Voltage	EMD	UPFC	600	500 kV transmission system with 100 MVA UPFC
Ref. [22]	Two-terminal	Voltage	ITD, EMD, S-transform, ESPRIT	UPFC	600	500 kV transmission system with 100 MVA UPFC
Ref. [23]	Single-ended	Voltage and current	DWT	UPFC	1000	4-machine 500 kV system

and fault parameters variations are considered for investigating the performance of proposed FLM. Significant operating conditions include variations in inception angles, references of UPFC, operating modes, sampling frequency and presence of noise. Form the numerical results, the efficacy of the prosed FLM is established.

In [3], intrinsic time decomposition (ITD) is used to develop a FLM for UPFC compensated system. For simulation, a 500 kV transmission system with 100 MVA UPFC is used. Voltage measurements obtained at two-terminals are utilized as input signals. ITD is used to decompose the signals in principle rotation components (PRC) and from the instant of peak of PRC1, ATTW information is extracted. The estimated ATTWs are used to locate faults using the concept of traveling waves. A sampling frequency of 600 kHz is considered. To test the performance of proposed FLM, system and fault parameters are varied. Modes of operation of UPFC and UPFC parameters are additionally varied to prove the insensitivity of FLM towards them. The results proved the efficient performance of the proposed FLM.

In [21], empirical mode decomposition (EMD) is used to propose a FLM for UPFC employed system. For simulation, a 500 kV transmission system with 100 MVA UPFC is used. Voltage measured at two-terminals are utilized as input signals. EMD is used to decompose the signals in intrinsic mode functions (IMFs) and from the instant of peak of IMF1, ATTW information is estimated. Fault location is calculated by utilizing the information of ATTWs at terminals. A sampling frequency of 600 kHz is considered. To test the performance of proposed FLM, system and fault parameters are varied. Different types of compensation and varying sampling frequency are considered additionally to examine the robustness of the proposed method. The proposed FLM is found to be robust and efficient.

In [22], different signal decomposition methods are used to detect ATTWs and consequently locating faults in UPFC compensated transmission system. For all simulations, a sampling frequency of 600 kHz is considered and voltage signals measured at terminals are used as input signals. Here, different operating modes of UPFC i.e., UPFC in power control mode, STATCOM mode and SSSC mode are considered to test the performance of FLMs. A comprehensive comparative assessment of few FLMs available in literature is carried out to identify better FLMs in context of estimation of fault location in FACTS compensated system. The performance of ITD, EMD, S-transform and ESPRIT based FLMs are analyzed in this study. EMD based FLM is found to be performing well in most of the considered cases. FLM based on S-transform is found to be producing unacceptable results for few test cases.

In [23], a single-ended traveling-wave method is proposed for fault location estimation in UPFC compensated system. Voltage and current signals are used as input signals. DWT is utilized to decompose signals in order to estimate ATTW. Estimated ATTWs are used for fault localization. Cooperative game approach is adopted to distinguish extracted traveling waves in this study. A mid-point connected UPFC of 100 MVA in 500 kV transmission system is used for simulation. A sampling frequency of 1000 kHz is considered throughout all simulations. The performance of proposed method is investigated for different operating conditions of the system including system operating under different modes of operation and varying location of UPFC.

A summary of prime characteristics of FLMs for series-shunt FACTS compensated system is tabulated in Table 4. From the table, it can be seen that mostly two-terminal FLMs are developed for series-shunt FCATS compensated system. Voltage signals are used as input signals for extracting information of arrival time of traveling waves. The reason behind selection of voltage signals is its less susceptibility toward transient features. In order to have higher accuracy, the signals are sampled at higher frequencies. Mostly, 500 kV transmission system is used for simulation.

As mentioned in Table 4, ITD and TEO are used to decompose modal voltage signals [22]. The modal voltage signals are decomposed using ITD to obtain first principal rotation component (PRC1) and TEO is applied on PRC1 to obtain energy signal. From the peak of energy signal, ATTW is estimated. A case study to illustrate the same is considered here as explained in [22]. A three-phase fault is initiated at 0.3 s at a fault distance of 111.30 km. The sampling frequency is 600 kHz. The line length is 200 km and wave speed is equal to 2. 849852126e5 km/s. Fig. 8 shows the working TEO assisted ITD based FLM for the mentioned test case. Fig. 8(a) shows the decomposition of aerial-mode voltage signal to obtain PRC1 via ITD and energy signal is obtained after applying TEO on PRC1 signal for bus B1. From this figure, ATTW is estimated from the peak of the energy signal and is found to be 0.303162 s. Similarly, for bus 2, ATTW is estimated from Fig. 8(b) and it is found to be equal to 0.303085 s. Using estimated ATTWs, estimated fault location *EFL* and corresponding percentage error *E* are calculated as follows:

$$EFL = \frac{200 - (2.\ 849852126e5(0.303085 - 0.303162)}{2} = 110.9244 \text{ km} \tag{8}$$

$$E = \frac{|111.30 - 110.9244\ |}{200} \times 100 = 0.1878 \tag{9}$$

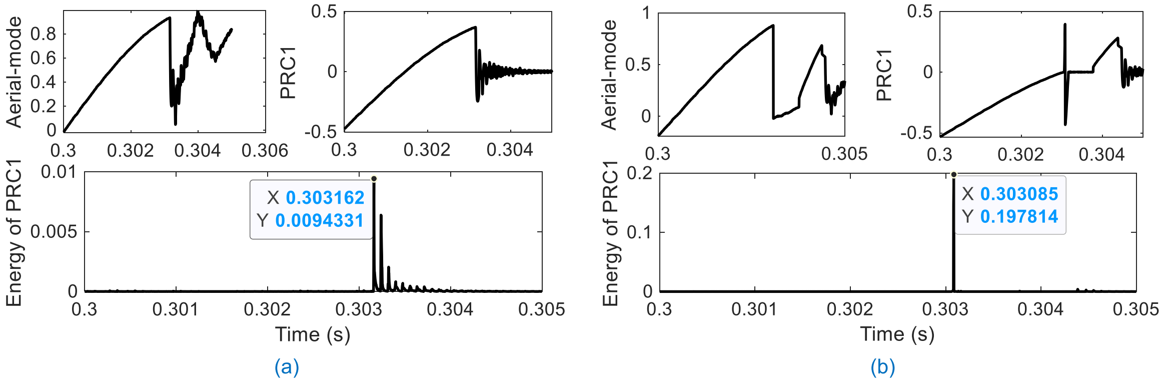

Fig. 8. TEO assisted ITD-based FLM for UPFC compensated system. (a) ATTW estimation for bus B1. (b) ATTW estimation for bus B2.

The percentage error is found to be 0.1878 which is well within acceptable limit of 1%.

Limitations and challenges of traveling-wave based methods

Following limitations are associated with traveling-wave based FLMS.

- Requirement of high sampling frequency for accurate fault location estimation.
- Involvement of high installation cost.
- Dependency of accurate arrival time estimation on wave-front value.
- Presence of taps in power lines decreases the values of signal traveling-wave.

Despite these limitations, traveling-wave based fault locators are practically used presently. Due to communication advancements, higher sampling rates are achieved without difficulty. Installation cost may go down in coming years. Efficient signal processing tools can be used to detect low wave-front values thereby enhancing the performance of fault locators.

Future research directions

In future, a signal processing tool with excellent time-frequency resolution can be used to decompose voltage and current signals. The decomposed signals will then be used to extract accurate ATTW information. Further, FLM is required to be developed considering uncertainties in power system. Presently, renewable power generation are integrated in conventional system. Therefore, FLM should be developed for FACTS compensated system in coordination with renewable energy penetration. The robustness of existing and newly developed FLMs must be examined for cross-country and evolving faults. As seen from the recent literature review, it is seen that the research related to development of traveling-wave based FLMs are less explored therefore, more research attention should be directed towards it. Further, it is expected that the market size of FACTS devices is going increase manifolds by 2025. Consequently, reliable protection and fault location schemes should be developed for FACTS compensated system.

Conclusion

In this article, a short but current literature survey is presented for traveling-wave based FLMs for FACTS compensated system. Traveling wave fault locators are very fast and presently are used in abundance. Basically, these locators estimate the arrival time of waves at terminals and from this information, calculate the fault location. Further, FACTS devices are used in transmission system to enhance its power transfer capability. In modern power system, the presence of FACTS devices are common. Therefore, traveling-wave based FLMs are required to be developed for FACTS compensated system. From the literature survey, it is concluded that aforementioned area of research is less explored so more attention should be directed towards development of traveling wave based FLMs for FACTS compensated system.

Ethics statements

N.A.

Data availability

No data was used for the research described in the article.

CRediT authorship contribution statement

Saswati Mishra: Conceptualization, Methodology, Software, Validation, Data curation, Writing – original draft. **Shubhrata Gupta:** Writing – review & editing, Supervision. **Anamika Yadav:** Conceptualization, Methodology, Software, Supervision, Writing – review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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