LMD-based fault detection scheme for TCSC compensated wind integrated transmission lines

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ABSTRACT

In this paper, a fast fault detection scheme is presented to detect the faults in thyristor-controlled series capacitor (TCSC) compensated transmission line connected with the large wind farms to export the electrical power to grid. The proposed logic utilizes the current information at the relay location and processes through the local mean decomposition technique to extract the magnitude features of the current. Cumulative sum of these features are computed for each phase currents to detect the faults in the transmission lines and further to classify the faulty phase in the system. The residual component of the current is used to detect the ground involvement in the faulty phase. The proposed method is tested during variety of faults by changing the nature of the fault using the fault parameters. Furthermore, the impact of the TCSC is also investigated along with the dynamic changes of the WF and their influence on the protection scheme. All the simulations are performed in MALTAB-Simulink software.

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1. INTRODUCTION

The global changes in the power sector increase the operational challenges of the power system particularly in protection area. However, the merits offered by the structural changes of the power system are more dominant compared to the challenges and better protection schemes are suggested by the researchers with the help of the intelligent tools [1]. The intermittent nature of the renewable energy sources like wind and solar trigger the voltage and power fluctuations leading to stability issues are minimized by flexible AC transmission systems (FACTS). Designing protection algorithms in such complex system is challenging and few works are available in the literature focusing to improve the performance attributes of the protection schemes in FACTS and renewable integrated power networks [2]-[15]. Furthermore, the operational challenges introduced by renewable energy sources and the specific protection challenges in FACTS and renewable-integrated networks need to address by the innovative solutions. Existing protection schemes in conventional power systems are not fully equipped to handle such complexities, and current research on protection algorithms for these systems is insufficient, revealing significant gaps in the literature available in [5]-[23]. Therefore, developing advanced protection algorithms that effectively address these complexities is necessary. This involves leveraging intelligent tools such as signal processing, artificial intelligence, and data analytics to enhance the performance of protection schemes, focusing on fault detection, isolation, and system recovery processes.

In general, the distance relays are popular to protect the transmission line networks. However, they are not reliable for the modern systems integrated with both WFs and FACT devices due to the dynamic variations in wind speed, power and level of compensation etc. In this context, adaptive distance relays are proposed in existing research studies [2]. Dubey *et al.* [2] proposed an adaptive distance scheme to enhance the performance of distance protection particularly during high resistance faults. The research analytically examines the effects of FACTS devices, such as static synchronous compensator (STATCOM) and static VAR compensator (SVC), when integrated with offshore wind farms on distance relay characteristics. The findings, verified through simulation, indicate that the under-reach issue is more severe with SVC systems, which also alter the line characteristics seen by the relay even in bolted faults. Furthermore, adaptive tripping characteristics for high resistance line-to-ground faults with shunt-FACTS devices, considering varying operating conditions, are necessary and addressed in [2]. Mohamed *et al.* [3], the distance relay performance is enhanced with adaptive settings in presence of TCSC. Another method is proposed in [4] for the WF integrated transmission lines in presence of TCSC. According to the work presented in [4], an innovative approach for enhancing fault detection and location determination in TCSC compensated lines connected to wind farms, utilizing fast discrete s-transform (FDST) based on travelling waves. The modal components of measured currents at each terminal using FDST to accurately detect the arrival time of the first travelling wave generated by a fault. This method identifies the faulted section by detecting the terminal with the fastest wave arrival time and estimates the fault location using a suitable distance index. Recently, transient monitoring index (TMI) based improved protection scheme is proposed in [5] to achieve 100% reliable metrices. The nonlinear relationship between power and speed of windmills, control logics of power electronic-based components interfacing with DFIG wind turbine generators, and the nonlinear operation of TCSC during faults adversely affect the performance of conventional distance relaying-based line protection schemes. The method derives a feature called TMI from three-phase currents received at the relay location for diagnosis of fault issues and employs a TMI-assisted support vector machine for fault classification. The effectiveness of the proposed scheme is validated through various fault and non-fault transients. Mohanty *et al.* [6], time-frequency analysis-based intrinsic time scale decomposition (ITD) method is used to detect the faulty phase in WF integrated transmission lines. Kumar *et al.* [7], empirical mode decomposition (EMD) is used to detect the faults. Overall, several signal processing techniques were extensively applied to detect various faults in transmission lines in presence of WFs. Recently, a detailed review is presented by Prasad *et al.* [8] discussed the application of distance, differential, intelligent relay schemes in WF integrated transmission line protection.

Apart from the distance relays, differential relays are so popular due to their merits over distance relays. Several new differential protection algorithms are available in the literature particularly suitable for the wind integrated transmission lines [9]. Over current relays with adaptive and optimal setting concepts are also suggested in the earlier works to protect the WF connected lines [10]. Furthermore, the support of the intelligent mechanisms enhances the abilities of the distance, differential and over current relay logics to improve the performance attributes of such schemes [8], [11]. For example, an innovative threshold setting concept is adopted in [12] to enhance the performance of the differential protection algorithm. All these aforementioned works are studied on the WF integrated transmission lines with or without TCSC. Other FACT devices like UPFC [13], STATCOM [14], and SVC [2] are also considered in the design of these algorithms [15]. The recent works concentrated on modified protection schemes in presence of both wind and FACT system integrated complexities [16]-[23]. These studies have proposed innovative protection schemes for integrating renewable energy sources along with FACT devices. Wang *et al.* [16], an adaptive auto-reclosing method for wind farms and STATCOM assisted power system is presented for active fault detection to improve system reliability during the uncertainties of the equipment. The operation of MOV-protected series compensators with wind power, emphasizing fault mitigation to enhance stability is provided in [17]. Keramat and Fazaeli [18], an adaptive protection method using PMU data for compensated transmission lines with high wind energy penetration, addressing real-time system adjustments is suggested. Costa [19], presented a method for real-time transient detection using boundary wavelet coefficients, improving fault isolation and system protection. A differential protection algorithm for transmission lines connected to large-scale wind farms, focusing on accurate fault detection and isolation is available in [20] and other related works in [21]-[23]. The computational burdens of these aforementioned schemes are further reduced with alternative algorithms which are simple in nature.

This paper introduces an integrated approach to detect the fault, to identify the faulty line and to classify the type of fault from the LMD features of the line currents information. The LMD of residual current component is also used as one feature of the proposed method to identify the ground involvement of the fault. This feature enhances the dependability of the algorithm during the remote end faults, high resistive faults, and high impedance arcing faults. The method is simple and robust in nature, produce fast detection and classification outputs during all the faults. The detail of the proposed approach is provided along with the numerous simulation studies to show the merits of the algorithm.

2. PROPOSED METHOD

The feature extracted from the instantaneous current information is useful to detect and discriminate the various events in the power system network. To extract such useful features from the raw measurements, several signal processing techniques such as discrete Fourier transform (DFT), wavelet transform (WT), and empirical mode decomposition (EMD) are preferred. In this paper, LMD is opted to extract the amplitude features of the current measurements. LMD is a time-based decomposition technique to enhance the features of the signals useful to detect the events and discriminate the abnormal conditions of the systems form the signal analysis [24]. In particular, the time-frequency distribution of the power system signal with weak fault features can be completely derived from LMD. The input signal, $i(t)$ is divided into n number of product functions (PFs) and one residual component $r_n(t)$together produce the original function as shown in (1) [25].

$$i(t) = \sum_{i=1}^{n} PF_i(t) + r_n(t) \quad (1)$$

Like EMD, the decomposition procedure of the LMD works based on finding the local maxima and/or minima of the given signal $i(t)$ to calculate the local mean and estimate the first PF using moving average filter and the process is terminated once a monotonic signal appeared after the extraction of n number of PFs.Among the available PFs, effective PF is needed to extract the weak fault features [18]. As the fault magnitude is large compared to normal pre-fault conditions, the first PF is preferable to detect the faults in the line connected to WFs using the (2).

$$PF_1^{phase}(k) > \theta \quad (2)$$

Furthermore, the cumulative sum (CUSUM) is adopted on PF_1 of three phases provide 3 CUSUM indices to detect the faults and faulty phase in the transmission line. The CUSUM process is expressed using the (3).

$$CUSUM_a(k) = CUSUM_a(k-1) + \max(PF_1^a(k) - \theta, 0) \quad (3)$$

When the CUSUM index exceeds 0, the faults are recorded, and faulty phase is identified to perform the classification of faults. Furthermore, the ground involvement is evaluated with the help of residual current component using the (4).

$$i_r(t) = i_a(t) + i_b(t) + i_c(t) \quad (4)$$

For A-g, A-B, A-C, A-B-g, A-C-g, and A-B-C, the index $CUSUM_a$ exceeds 0 after few milliseconds from the fault initiation. For B-g, A-B, B-C, A-B-g, B-C-g and A-B-C, the index $CUSUM_b$ exceeds 0 after few milliseconds from the fault initiation. ForC-g, B-C, A-C, B-C-g, A-C-g, and A-B-C, the index $CUSUM_c$ exceeds 0 after few milliseconds from the fault initiation. For example, the indices corresponding to phase-A and phase-B exceed the 0 value in case of A-B and A-B-g faults. To distinguish these two similar faults, the residual component helps which exceeds the threshold for A-B-g fault only. Therefore, the proposed logic detects all types of the faults and classifies the type of fault irrespective of the fault parameters such as location, resistance and inception time. The mechanism provided in the paper is simple and CUSUM indices exceeds zero during the disturbances and all types of the faults are recorded based on the CUSUM information. The detection of grounding faults is directly examined by using the residual component of the instantaneous current data.

3. RESULTS AND DISCUSSION

3.1. Test system

To check the performance of the proposed detection and classification protection scheme, a test system shown in Figure 1 is simulated in MATLAB/Simulink. The transmission line of 320 km connects the large WF to grid via proper voltage levels. The capacity of the WF is 60 MW. The grid side voltage is 500 kV. The wind side voltage is step up to 500 kV from 575 V using the transformers as shown in Figure 1. The details of the test system are available in [7]. Furthermore, TCSC is placed in the line to enhance the stability of the system and 75% compensation is fixed in this study. The protection unit of the system is transmission line connected between the buses G, W and the relay is placed at G. The three phase currents and voltages are measured using the current and voltage transformers at bus G which is connected to grid are used to design the proposed protection algorithm. Instead of both measurements, only current measurements are used in this work are processed through LMD to extract the amplitude features. CUSUM indices are computed from the amplitude information and faults are recorded.

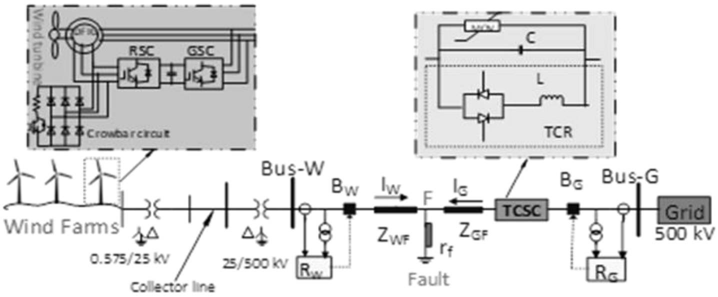


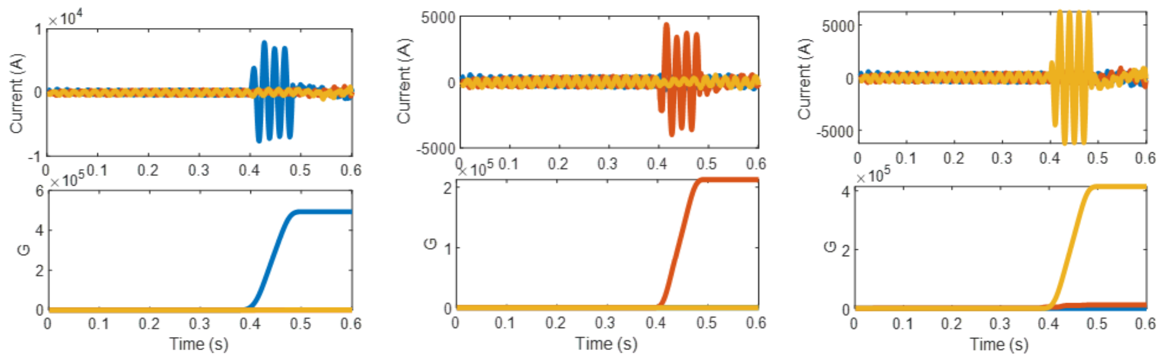
Figure 1. Single line diagram of the test system [7]

3.2. Simulation results

The effectiveness of the proposed technique is assessed with variety of simulation studies by varying the nature of the faults. The studies include various types of faults such as line-to-ground, line-to-line, line-to-line-ground and triple line faults simulated at different fault operating conditions such as location of the fault, fault resistance, ground resistance, inception angle of the fault. Furthermore, the intermittent nature of the wind system is investigated on the performance of protection logic. Other cases like remote end fault, high resistive fault, and high impedance arcing fault are also simulated on the test system to validate the efficacy of the method.

3.2.1. Different types of faults

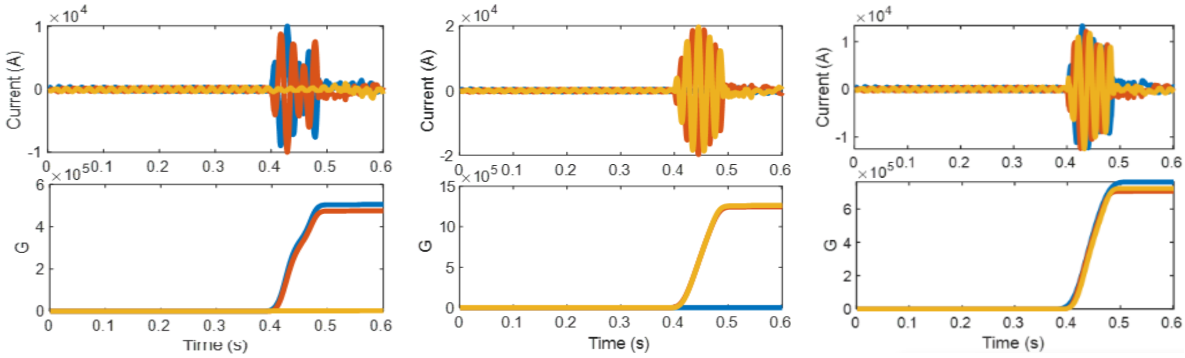
The line-to-ground faults frequently occurred in the transmission system and therefore, the logic is tested on the A-g, B-g and C-g faults to validate its performance. For A-g fault, 100 km is the location of the fault with fault resistance of 20Ω. For B-g fault, 180 km is the fault location and fault resistance is 10Ω. For C-g fault, 70 km is the fault location and 40Ω is the fault resistance. The current measurements along with the proposed fault detector indices are presented in Figure 2. From the responses of the protection logic, it is understood that the faults are recorded within one full cycle and phase selection is also possible from the outputs of the CUSUM indicators. In Figure 2(a), the $CUSUM_a$ exceeds zero after fault inception and rest of the indicators are zero. This observation is repeated with other indicators based on the types of the fault show the adaptability of the logic for fault classification. In Figure 2(b), the outputs of the scheme are presented for the B-g fault and for C-g fault, the response is provided in Figure 2(c). Due to ground involvement in line-to-ground faults, the residual component also exceeds the preset threshold and helps to classify the faults.



(a) (b) (c)

Figure 2. Response of the scheme along with the input measurements for; (a) A-g, (b) B-g, and (c) C-g faults

This investigation is further extended to A-B, B-C-g and A-B-C faults and the results are plotted in Figure 3. For A-B fault, 200 km is the location of the fault with fault resistance of 1Ω. For B-C-g fault, 130 km is the fault location and fault resistance is 5Ω. For A-B-C-g fault, 160 km is the fault location and 8Ω is the fault resistance. The responses of the proposed scheme during the A-B, B-C-g, and A-B-C-g faults are presented in Figure 3(a), Figure 3(b), and Figure 3(c) respectively. Irrespective of types of faults and their diverse parameters, the scheme produces fast detection and classification outcomes with 100% accuracy.

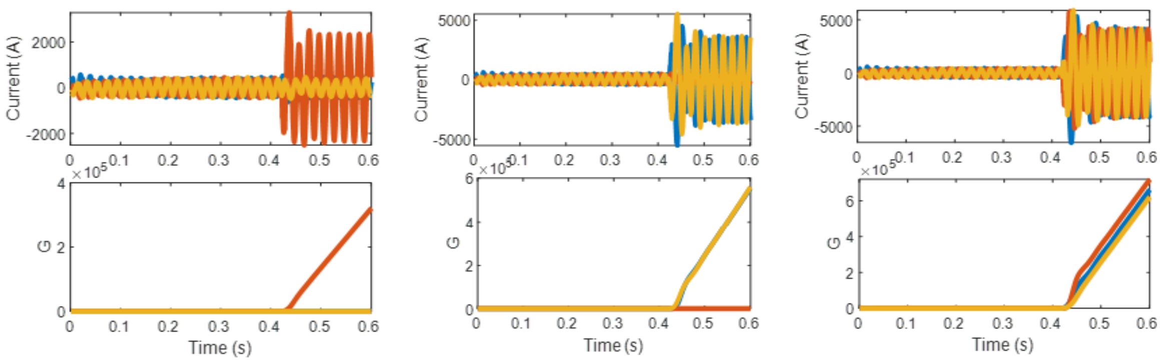


(a) (b) (c)

Figure 3. Response of the scheme along with the input measurements for; (a) A-B, (b) B-C-g, and (c) A-B-C-g faults

3.2.2. Remote end faults

The traditional distance relays placed at G are failed to detect the faults occurring beyond the 80% of the section of the line are categorized as remote end faults. The protection logic suggested in this paper is tested under variety of the remote end faults by varying the type of fault, location of fault, inception time of the fault and fault resistance. Initially B-g fault is simulated in the test system with fault location, inception and resistance of 275 km, 0.42 sec, and 10Ω respectively. Later the fault type is changed to A-C and A-B-C-g with same fault parameters. The responses of the scheme against the remote end B-g, A-C, and A-B-C-g faults are presented in Figure 4(a), Figure 4(b), and Figure 4(c) respectively. Two critical observations are reported after the simulation studies of the aforementioned cases. First, the dependability of the scheme is extremely good for the remote end faults and the classification outcomes of the method are also acceptable. Therefore, the proposed logic is well suited to detect the typical faults along with the regular events.

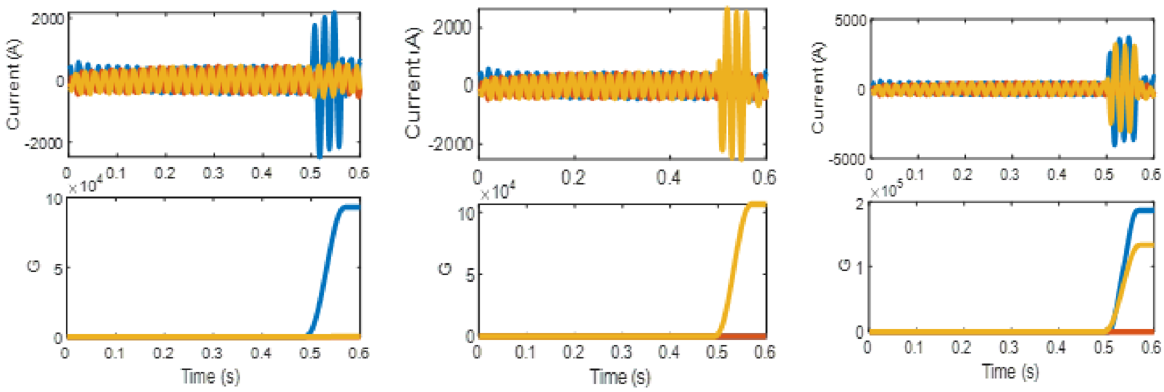


(a) (b) (c)

Figure 4. Response of the scheme for remote end faults; (a) B-g, (b) A-C, and (c). A-B-C-g faults

3.2.3. High resistive faults

The impedance seen by the distance relays should be within the zone settings to detect the faults in the transmission lines irrespective of the structural changes of the power system model. However, the faults with high fault resistance/impedance are failed to detect by the traditional relays and therefore more reliable schemes are necessary. The proposed method is tested under this case with three different fault scenarios. In first case, an A-g fault is initiated at 0.5 sec with a fault resistance of 100Ω and located at 165 km from the grid bus G. In second case, C-g fault is initiated at 0.5 sec with a fault resistance of 120Ω and located at 45 km from the grid bus G. Finally, A-C-g fault is simulated with fault parameters of 0.5 sec, 80Ω, and 135 km. The responses of the method are presented in Figure 5(a), Figure 5(b), and Figure 5(c) for all the three cases. The proposed scheme produces quick detection outputs for the high resistive faults like low resistance faults. This is one significant merit of the algorithm compared to existing impedance-based relay logics. Furthermore, the phase selection is also possible with the proposed scheme since the CUSUM indicator of faulty phase respond for the fault involving with the same phase.



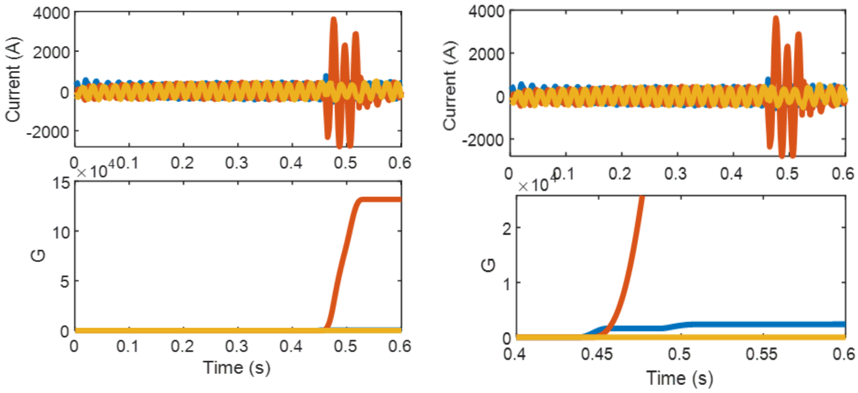
(a) (b) (c)

Figure 5. Response of the scheme for high resistance faults; (a) A-g, (b) C-g, and (c) A-C-g faults

3.2.4. Wind intermittency

The test system integrated with the large WFs offers voltage and power fluctuations and therefore the relay logics are mal operated during the dynamic and intermittent conditions of the system presented in Figure 6. To check the performance of the protection logic during variable conditions of the wind system, wind speed is changed from its nominal value of 15 m/s to 20 m/s and faults are simulated at that condition.

Under this case, B-g fault with 240 km as location of fault initiated at 0.46 sec and offers a fault resistance of 10 Ω is simulated and the current data is processed through the proposed LMD protection scheme to verify the outputs. The response is presented in Figure 6(a). Furthermore, the wind speed condition is changed from 15 m/s to 10 m/s and the fault is simulated Figure 6(b). In both cases, the proposed logic is able to detect the faults without changing the preset conditions of the algorithm. Since the change in wind speed condition deviates the power system signals significantly and therefore the phase selection is difficult for certain faults. It is evident from the second case of Figure 6 where the CUSUM indices of phase A and C exceeds 0 along with B for the fault B-g. However, detection of faults is possible irrespective of the fault cases even in dynamic conditions of the system.



(a) (b)

Figure 6. Response of the scheme for B-g fault for wind speed of (a) 20 m/s and (b) 10 m/s

3.3. Discussions and comparisons

The investigation into fault detection within transmission systems has underscored the critical importance of fault parameters such as fault location, inception, and fault path resistance. The proposed fault detection logic was rigorously tested on a variety of faults, revealing its robust performance. For line-to-ground faults, specific cases were examined: an A-g fault at 100 km with a resistance of 20Ω, a B-g fault at 180 km with 10Ω, and a C-g fault at 70 km with 40Ω. These tests showed that faults were detected within one full cycle, and the phase selection was accurately achieved through the CUSUM indicators, which adapted to different fault types. Extending the study to A-B, B-C-g, and A-B-C faults, with fault locations at 200 km, 130 km, and 160 km and resistances of 1Ω, 5Ω, and 8Ω respectively, further validated the method's adaptability. Traditional distance relays, which struggle with remote end faults beyond 80% of the line, were outperformed by the proposed logic when tested with B-g, A-C and A-B-C-g faults at 275 km, 0.42 sec, and 10Ω. High-resistance faults posed another challenge for traditional relays, but the proposed method efficiently detected faults such as an A-g fault at 165 km with 100Ω, a C-g fault at 45 km with 120Ω, and an A-C-g fault at 135 km with 80Ω, all initiated at 0.5 sec. The results consistently demonstrated quick and reliable fault detection, highlighting the method's superiority in both typical and high-resistance fault scenarios, while also enabling precise phase selection. The comparisons of various signal processing tools over LMD are performed against typical events and the accuracies of the methods are tabulated in Table 1. Table 1 provides a comparison of classification accuracies across four techniques. Each technique was tested on 29 typical cases, and the results indicate notable differences in accuracy. DFT achieved a classification accuracy of 89.65%, correctly identifying 26 cases while misclassifying 3. Both WT and EMD performed equally well, each accurately classifying 27 out of 29 cases, resulting in a slightly higher accuracy of 93.10%. LMD outperformed the other techniques, achieving the highest accuracy of 96.55%, with 28 true cases and only 1 false case. These results suggest that LMD is the most effective technique for classification in this comparison, followed closely by WT and EMD, while DFT lags slightly behind.

Table 1. Comparisons of classification accuracies of the various techniques

Technique	Total cases	True cases	False cases	Accuracy (%)
DFT	29	26	3	89.65%
WT	29	27	2	93.10%
EMD	29	27	2	93.10%
LMD	29	28	1	96.55%

4. CONCLUSION

An LMD-based protection scheme is presented to detect and classify the faults in the transmission lines connected to WFs. The scheme produced reliable detection metrices for various faults irrespective of the nature of the fault, type of fault and fault parameters such as fault location, inception time and fault resistance. The dynamic changes in wind speed are not affecting the performance of the protection logic is another merit. With the single end current measurements, the remote end and high resistance faults are recorded correctly by the LMD-based protection scheme. Only for few typical fault cases at extreme operating conditions, the classification accuracy is low and therefore intelligent schemes are suggested in future work to improve the classification attributes at extreme operating conditions.

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