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Efficient Fault Detection Based on Localization and Classification of Transmission Line Using Morlet Discrete Neuro Fuzzy Logic Wavelet Transform

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Abstract: Transmission line faults are the main causes of interruption in power supply system. The fault on transmission lines affects the reliability and stability of the system. Fault identification, location using Synchronized Phasor Measurements has become highly significant, as they were capable of locating faults with its proven higher amount of accuracy. However, Synchronized Phasor Measurements have revealed some of its drawbacks in the conventional fault identification, location system. To improve the accuracy of fault detection, localization and classification of transmission line, a method called Morlet Discrete Neuro Fuzzy logic Wavelet Transform (MDFWT) is proposed. Initially, Morlet Envelope Spectrum (MES) Power wavelet transform is applied to detect faults on the measured frequencies and time of the modulating components. MES power wavelet transform in MDFWT method consists of complex exponential carriers with a multiplied Gaussian window to detect the faults. Detected faults are localized using the Discrete Wavelet Transform (DWT). DWT with Boltzmann entropy theory locates accurately the position of the fault on the transmission line. Finally the classification of transmission line faults in the MDFWT power system is carried out using the Neuro Fuzzy logic wavelet transform. The neuro fuzzy logic wavelet transform uses the if-then rules to classify the faults in an efficient manner with the highest reliability. Neuro fuzzy logic set in MDFWT method highlights the acquired knowledge for easy diagnosis of faults on the transmission line. The experiments are conducted on the factors such as fault detected error rate, fault localization accuracy and fault classification rate.

Key words: Morlet envelope spectrum, Boltzmann entropy theory, discrete wavelet transform, neuro fuzzy logic, gaussian window, fault localization

INTRODUCTION

Faults occur in the transmission lines due to various reasons like wind, thunderstorms, short circuits and so on. Faults have to be removed in the power lines as early as possible to ensure continuity of supply (Saravanababu *et al.*, 2013). Accurate fault detection, localization and classification under different power system operating constraints are the most significant requirement. Adaptive Fault Location (AFL) (Mohammed *et al.*, 2014) presented a localization algorithm for power transmission system on the basis of synchronized phasor measurements. In order to increase the level of accuracy, the localization measurement was derived from Phasor Measurement Units (PMUs). However, certain issues like accurate fault classifications were not handled in an efficient manner using Synchronized Phasor Measurements.

Fault detection and classification has to be determined to continue the system from intermittent faults and provide solutions to the same. A new technique called as Wavelet Singular Entropy (WSE) (He *et al.*, 2010) is presented for efficient fault detection and classification. WSE provides certain advantages in power transmission systems and automatically extracts the features in high noise and low magnitude fault transients, but did not include the provision for higher amount of reliability on efficient localization of transmission line faults. An efficient fault detection mechanism based on the Clonal Selection Programming (CSP) (Ha *et al.*, 2013) was designed for detection and analysis of fault present in induction machine. CSP used a multi-thread model designed on the basis of master/slave style to improve the level of accuracy. Though accuracy was improved, it is limited to induction machine only.

Space Phasor and Hilbert Huang Transform (SPHHR) (Bernadic and Leonowicz, 2012) were designed to identify

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the location of fault in power networks. SPHHR used a three phase fault voltage to convert complex values to simple fault travelling wave to provide accuracy in determining the fault. Though accuracy was emphasized but the frequency was the main constraint in this model.

Fault Diagnosis System (FDS) (Mohamed *et al*., 2010) was designed for power transmission lines using two different types of protection zones. The design of FDS not only reduced the cost of the system, but also minimized the complexity involved in the designing.

An efficient indoor localization method was designed by Ha *et al*. (2013) using Zigbee sensor nodes. This Zigbee sensor node classified the Link Quality Indicator (LQI) patterns using a target node and multiple reference nodes to identify the fault location in indoor environments improving the accuracy of the localization method. But due to the signal interferences with walls, windows, doors and so on RSS based approach is difficult to apply. Han *et al*. (2014) localization algorithms were compared with large scale underwater networks that provides an improved method for localization.

In this study, fault detection, localization and classification technique on a power transmission line based on vehicle classification techniques with Morlet Discrete Neuro Fuzzy Logic Wavelet Transform (MDFWT) method have been investigated. The MDFWT method uses Morlet Envelope Spectrum (MES) Power Wavelet Transform for efficient fault detection based on the frequency and time of the modulating components. Followed by this, the detected faults are localized using the discrete wavelet transform. Finally, neuro fuzzy logic wavelet transform is applied for efficient classification of faults.

Literature review: The transmission and distribution lines are the most important links for continuity of supply from generating station to customers. Research works are going in larger numbers in this area of transmission line fault analysis. Adaptive Network Based Fuzzy Inference System (ANFIS) (Sadeh and Afradi, 2009) provided a mechanism for locating faults on the transmission line. Though classification accuracy and error rate was drastically improved, it has not applied to several scenarios. A method using Support Vector Machines (SVM) (Kabaoglu, 2015; Gan *et al*., 2009) was designed for fault diagnosis and reconfiguration for several predetermined faults using an online controller and was effectively applied in various scenarios.

A novel method called RSSI based Smooth Localization (RSL) algorithm (Wang *et al*., 2014) was designed to increase the accuracy of the decision point, identification of path matching error and to identify the ratio of wrong jump to evaluate the efficiency of localization in a transmission line. The RSL algorithm identified and measured the position and evaluated the entity by addressing the weights for all RSSI information to make localization smooth. Though smoothness was achieved, but the delay increased with the increase in power transmission lines. To address the problems like delay, diffraction and scattering models (Xing *et al*., 2014) which were included initially and identified the target on the basis of signal strength followed by the target and localized in several modes.

S-Transform (ST) and Support Vector Machines (SVMs) (Li *et al*., 2010) was designed for effective classification and identification of fault in power transmission line using three line signals with the help of zero sequence current to increase the level of accuracy. Though, accuracy was improved but not on different operating conditions. An efficient method for classification of fault on transmission lines was presented using fuzzy logic (Mahanty and Gupta, 2007) with three phase currents. The advantage of this method was that it was implemented for different fault conditions at several angles on different operating conditions. Redondi *et al*. (2013) several localization methods were designed for identification and determination of location in Wireless Sensor Networks (WSNs).

MATERIALS AND METHODS

Morlet discrete neuro fuzzy logic wavelet transforms of power transmission line: One of the focal points of the research work on a power transmission line is the efficient detection, localization and classification of fault to improve reliability and stability of the system. The objective of fault analysis using the proposed Morlet Discrete Neuro Fuzzy Logic Wavelet Transform (MDFWT) is to provide adequate information about the location of faults and fault type. Further, by the application of Morlet Envelope Spectrum (MES) based power wavelet transforms, it efficiently detects the fault. Morlet Wavelet power spectrum is depicted in Fig. 1.

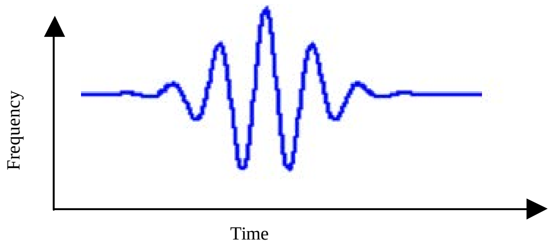

Fig. 1: Morlet wavelet power spectrum

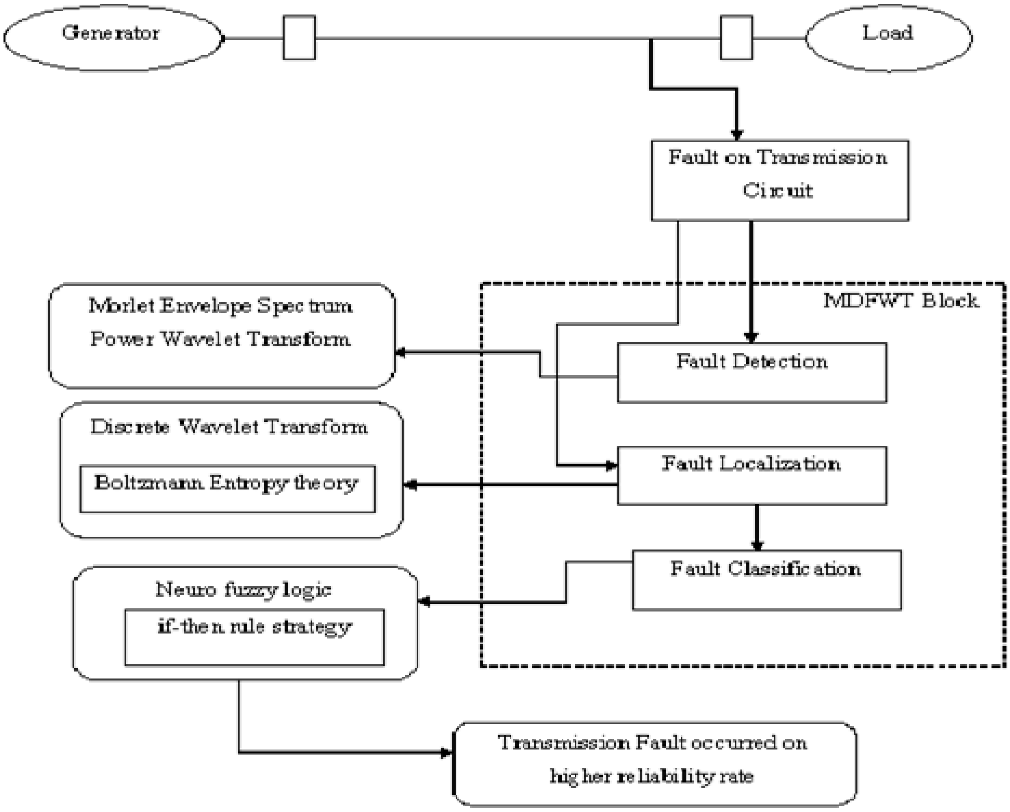

Fig. 2: Architecture of MDFWT method

It is a type of wavelet transform which is highly powerful to detect the faults with the help of time frequency analysis. Fault signal is systematically detected using the complex three phase circuits with frequency domain value computation. MES handles the transmission lines in a power system by detecting the analytic version signal of the real value where the actual fault occurred. The architecture of MDFWT is depicted in Fig. 2.

Power transmission line: As in Fig. 2, the fault points are detected on the transmission line. Firstly, MDFWT method detects the fault using the Morlet Envelope Spectrum with multiplied Gaussian window. The MES handles the power circuit by using the time frequency value. Secondly, MDFWT locates the transmission line fault using the Discrete Wavelet Transform with Boltzmann entropy theory. The final task is the design of MDFWT method to classify the faults using Neuro Fuzzy logic system. The neuro fuzzy logic with if-then strategy constructs the fault classification system.

Morlet envelope spectrum power wavelet transform: The morlet envelope spectrum based fault detection extracts the unusual modulating signal from an amplitude modulated power signal. Envelope analysis with vibrating signal extracts the faulty area in the transmission line. The goal of the enveloping spectrum approach in MDFWT method is to replace the oscillation caused by each impact with a single pulse over the entire period of the operation. The envelope spectrum analysis on MDFWT method is performed using Gaussian windowing function. The Morlet envelope system on three phase power circuit obtains the value of time and frequency using the accelerometer. In MDFWT, Morlet envelope wavelet transform with single Gaussian windowing function is defined as:

$$\psi(t)=\mathrm{EXP}(i,f_1,t)\mathrm{EXP}\left(-\frac{t^2}{2\sigma^2}\right) \tag{1}$$

Equation 1 $\Psi(t)$ denote the Morlet power wavelet transform with frequency fat transform t of power

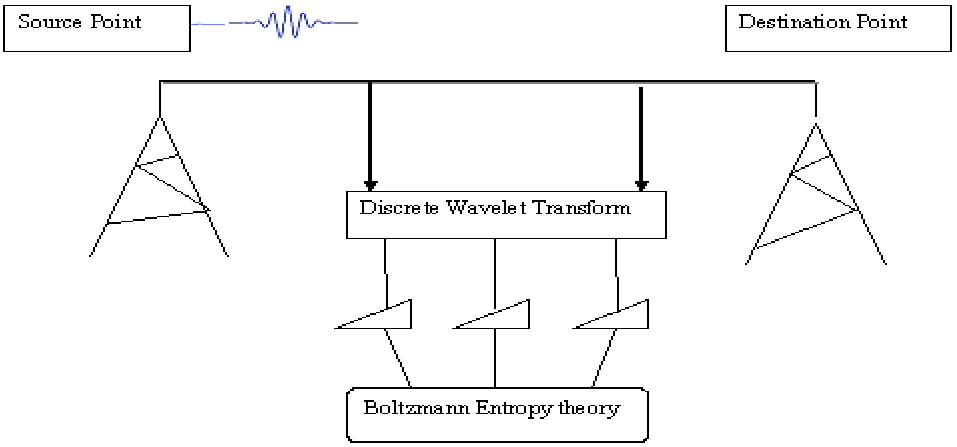

Fig. 3: Fault Localization using MDFWT method

transmission line I, σ Symbolizes the measure of single faults on the transmission line i. The usage of the Gaussian windowing function reduces the time bandwidth product in MDFWT method:

$$\text{Time bandwidth product} = \sigma \times \frac{1}{\sigma} = 1 \qquad (2)$$

The application of Gaussian windowing in MDFWT reduces the time bandwidth product for detecting the faults. The Gaussian windowing observed signal over the transmission line at a measured time interval and gradually reduces it to zero. In MDFWT method, multiple Gaussian window function is the process of multiplying the vibration signal on transmission power signal. The Morlet waveform detects the fault on the transmission path using the multiple Gaussian window function on x and y points, as:

$$\psi(x, y(t)) = \frac{1}{x}\exp\left[i f_1\left(\frac{t-y}{x}\right)\right] \times \exp\left[-\left(\frac{t-y}{x}\right)/2\sigma^2\right] \qquad (3)$$

The transmission line on the path x to y is multiplied by a Gaussian window function using the MDFWT method. When $f_1 = 2\pi$ where the Morlet wavelet oscillation is checked to identify the central frequency varying time domain. The Time frequency domain characteristics of multiple Gaussian window functions are analysed to determine multiple faults on the power transmission path. Gaussian window functions produce the choice of detection where detection denotes the detecting of the desired vibrating signals.

Discrete wavelet based fault localization: Once the fault on a power transmission line is detected, fault localization is performed which refers to the ability to spot the geographic position on the transmission line. Discrete wavelet transforms based fault localization on the power transmission line is used to accurately locate the fault in MDFWT method. Discrete wavelet locates the faults based on the dissimilarity between its time and frequency domains. The discrete wavelet transform on power signal p (t) is defined as:

$$\delta(p, t) = \int p(t).\psi(x, y(t)).dt \qquad (4)$$

Where:

$\delta(p, t)$ = Denotes time variance of the power signal to locate the faults

$\Psi(x, y(t))$ = Take transmission path with multiple faults to locate the faults accurately using the discrete transform

Multiple faults on the transmission line are accurately located using boltzmann entropy. Fault location in MDFWT transmission line is depicted in Fig. 3. Figure 3 depicts the fault localization in MDFWT using boltzmann entropy theory. The power system of 'M' fault occurrence on the transmission line with entropy 'E' is localized in MDFWT with the Boltzmann entropy theory defined as:

$$E = C\log(M)$$

here, 'C' is the Boltzmann constant = 1.38062×10^{-23} JK^{-1}. Boltzmann entropy in MDFWT method shows the relationship between entropy and the number of fault position occurring on the power transmission line.

Neuro fuzzy logic based fault classification: Finally, with the spotted geographic position on the transmission line, MDFWT uses a Neuro Fuzzy logic system to significantly

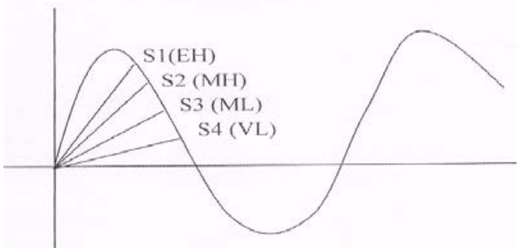

Fig. 4: Waveforms for four different faults

classify the fault types with the simple if-then rules. The input considered for experimentation is seven transmission lines with the frequency ranging from 0.5-3.5 Hz. The training algorithm used in this work is Neuro fuzzy logic based algorithm. The training and test data of Neuro fuzzy logic range seven fault types measured at 20 and 140 km. The membership function included in the MDFWT method as in Fig. 4:

- Lower amplitude, Very Low (VL) fault
- Short duration, Medium Low (ML) fault
- Fast decaying, Medium High (MH) fault and
- High frequency current signals, Extremely High (EH) faults

With the application of Neuro fuzzy logic based fault classification system, MDFWT handles multiple faults and also classifies the faults effectively. Neuro Fuzzy set implements if-then associations and set of rules along with entropy membership value on the power transmission line. The power transmission line faults are classified as lower amplitude, short duration, fast decaying and oscillating type of high frequency current signals. The entropy value provides various ranges. Based on the value of entropy, the faults are classified in MDFWT using Neuro Fuzzy Logic System.

As shown in the Fig. 4a, the MDFWT fault classification stage is performed using the if-then strategy. For fault classification, the MDFWT method contains the ratio of the sequence where lower amplitude implies Very Low (VL) fault, short duration implies Medium Low (ML) fault and fast decaying implies Medium High (MH) fault and high frequency current signals as Extremely High (EH) faults. Multiple faults on power transmission line are handled with a Neuro-fuzzy classifier. With the application of Fuzzy logic in MDFWT method, the response time is reduced considerably when compared with existing systems.

RESULTS AND DISCUSSION

Experimental evaluation: In order to make a correct detection, localization and classification of the power transmission line, the experiment is conducted on the MATLAB platform. The time, voltages and current data are sampled at 150 Hz. For a system running at 60 MHz and is sampling at 150 Hz, 6×10^5 cycles are provided between each monitoring state to complete all the necessary operations to perform the fault detection. The fault localization accuracy is also measured to more accurate the geographic location of the signal point where a fault has occurred.

Table 1: Comparison of fault detected error rate on power transmission lines with respect to frequency

	Fault detected error rate (%)		
Frequency (Hz)	MDFWT method	AFL	WSE
0.5	23.45	31.48	39.53
1.0	27.5	35.53	43.58
1.5	28.25	36.28	42.33
2.0	30	38.03	46.33
2.5	31.35	39.38	47.43
3.0	32.45	40.48	48.58
3.5	35	43.4	51.54

The fault classification requires the use of three identical networks, one per phase, so it is necessary at least 2×10^5 cycles to run the fault classification process. As a result, it implies that activation function is enough to obtain a proper response time. The results of Morlet Discrete Neuro Fuzzy Logic Wavelet Transform (MDFWT) method is compared with the existing Adaptive Fault Location (AFL) (Mohammed *et al*., 2014) algorithm and Wavelet Singular Entropy (WSE) (He *et al*., 2010). Experiment is conducted on the factors such as fault detected error rate, fault localization accuracy, power fault classification rate, system response time.

The range of frequency that is measured in terms of Hertz (Hz) are chosen initially as 0.5 and then increased in step to 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 as described Table 1. The best performance is achieved by using the method MDFWT and the optimal amount of fault detected error rate on a power transmission line was found to be at 2.6 Hz. In this learning strategy, the fault detected error rate gets increased. The MDFWT method requires large training sets and long training time, but for experimental purpose, we have considered till 3.5 Hz. Also, when the power transmission line is higher, the fault detected error rate gets reduced. The fault detected error rate for the proposed MDFWT method and two other existing methods AFL (Mohammed *et al*., 2014) and WSE (He *et al*., 2010) is presented in Table 1.

In a perspective to evaluate the fault detected error rate of the proposed method, we simulated in three phase circuits using the accelerometer with frequency $f_1 = 0.5$ Hz -$f_7 = 3.5$ corresponding to the time bandwidth product as illustrated in Fig. 5. The output of the proposed fault

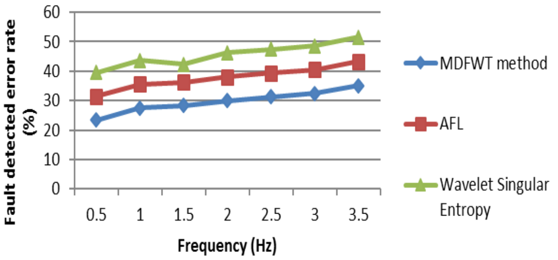

Fig.5: Variation of the fault detected error rate of MDFWT method for different frequency ranges

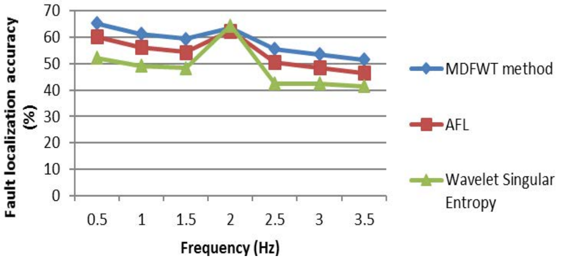

Fig. 6: Comparison chart of the fault localization accuracy, using the proposed Neuro fuzzy logic based algorithm performance in the network

the proposed method, MDFWT with that of the two state of the art methods AFL (Mohammed *et al*., 2014) and WSE (He *et al*., 2010) are presented in Table 2. In order to show the fast convergence of the proposed MDFWT method, under the influence of different detected error rate converges to 35% at frequency f_1 = 3.5 to the AFL and WSE whose fault detected error rate converges to 43.4 and 51.54% respectively. This is observed due to the application of morlet envelope spectrum based fault detection that in a way efficiently detects the unusual modulating signal using the amplitude modulated power signal by minimizing the fault detected rate by 24-34% when compared to AFL. In addition, using Gaussian windowing in MDFWT minimizes the time bandwidth product for detecting the faults and as a result, the fault detected error rate is minimized by 47-68% when compared to WSE respectively.

In order to evaluate the performances of the proposed fault localization accuracy of power transmission line, we consider various frequency ranges that are taken into account during the training process. The scenarios observed during training process are subjected under various fault conditions such as Very Low (VL) fault, short duration as Medium Low (ML) fault, fast decaying as Medium High (MH) fault and high frequency current signals as Extremely High (EH) faults.

Table 2: Summary of the results obtained in fault localization towards accuracy with different frequency measures

	Fault detected error rate (%)		
Frequency (Hz)	MDFWT method	AFL	WSE
0.5	65.21	60.18	52.16
1	61.28	56.25	49.23
1.5	59.35	54.32	48.30
2	64.36	62.38	63.41
2.5	55.45	50.42	42.40
3	53.52	48.49	42.47
3.5	51.55	46.52	41.50

Table 3: Results of fault classification with varied fault types, each fault tested in the range of kilometres

Fault types (each fault tested in km)	Power fault classification rate (%)		
	MDFWT method	AFL	WSE
20	1.250	1.200	1.100
40	1.285	1.235	1.115
60	1.315	1.285	1.165
80	1.345	1.295	1.175
100	1.380	1.330	1.210
120	1.415	1.365	1.245
140	1.450	1.400	1.300

The test results of frequencies, fault localization with entropy E localized using Boltzmann Entropy constant, 1.38062×10^{-23} JK^{-1}a fault occurrence at time 40 m sec was simulated as depicted in Fig. 6. We noticed that the proposed Neuro fuzzy logic based algorithm makes it possible to locate the fault with a good accuracy at faster convergence time. The observed fault localization accuracy rate at time t = 20 m sec is 59.35% with an observed frequency of 1= 1.5 Hz in the proposed MDFWT method, where at an accuracy rate of 54.32 and 48.3% was observed at time t = 20 ms for frequency 1= 1.5 Hz in AFL and WSE methods respectively. Thus, it is clear that the proposed MDFWT method can accurately locate the fault on a power transmission line than the other two state of the art methods. This is because the Discrete wavelet transforms based fault localization on the power transmission line in MDFWT method helps to accurately locate the fault based on the dissimilarity between its time and frequency domains and therefore increases the fault localization accuracy by 1-9 and 1 -0% when compared to AFL (Mohammed *et al*., 2014) and WSE (He *et al*., 2010) respectively.

A large number of training data for different MDFWT based fault detection, localization and classification were generated using MATLAB software taking into account various fault scenarios subjected under different fault types with each fault tested in kilometre. Thus, the simulated fault numbers for the method MDFWT ranges between 20 and 140 km. Table 3 tabulates the parametric measure used to provide the training data sets

Table 4: Results of system response time at various frequencies

	System response time (ms)		
Frequency (Hz)	MDFWT method	AFL	WSE
0.5	25.32	35.27	39.66
1.0	28.15	38.12	42.01
1.5	31.35	41.27	47.26
2.0	34.55	44.51	52
2.5	37.25	47.21	55.35
3.0	40.21	50.17	61.25
3.5	42.52	52.48	68.35

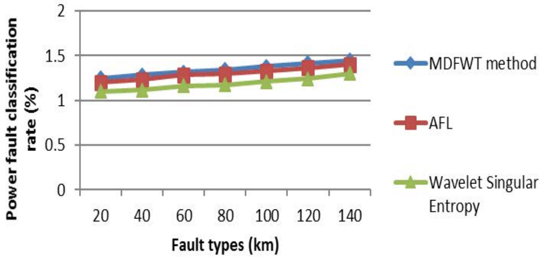

Fig. 7: Fault classification curve with respect to 7 fault types, each fault tested in kilometres

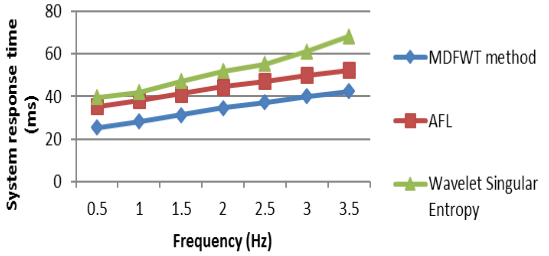

Fig. 8: System response time graph of the system with different frequency range using MDFWT method

and test models evolved for the proposed MDFWT method with two state of the art methods AFL (Mohammed *et al*., 2014) and WSE (He *et al*., 2010). In Figure 7, the power fault classification rate is symbolized using the method MDFWT and compared with two other methods AFL (Mohammed *et al*., 2014) and WSE (He *et al*., 2010). The fault classification rate was observed under different fault conditions with respect to distance, (i.e., measured in terms of km). Figure 7 is used as a graphical evaluation for better clarification. From the Figure 6 it is illustrated that the rate at which the power fault classification is classified is higher than that of the other methods. This is because, the method MDFWT uses a neuro fuzzy logic system in order to significantly classify the fault types with the simple if-then rule that results in the improvement of power fault classification rate by 2-4% when compared to AFL. In addition, the Neuro Fuzzy set implements if-then associations and set of rules along with entropy membership value on the power transmission line, resulting in increasing power fault classification rate by 10-13% when compared to WSE.

Table 4 presents the effect of the system response time on the proposed MDFWT method and comparison made with two other methods, AFL (Mohammed *et al*., 2014) and WSE (He *et al*., 2010). Indeed the system response time is measured with respect to different frequency ranges between 0.5 and 3.5 Hz considered for experimental evaluation. The system's response time under different frequency level is presented in Fig. 8. These results proved that by the coordination of the multiple faults on power transmission line using the Neuro fuzzy classifier, the stability of the power transmission line is significantly improved compared to the AFL (Mohammed *et al*., 2014) and WSE (He *et al*., 2010) methods, respectively. This is because with the help of time, frequency analysis using the proposed MDFWT method, on detecting the faults, the system response time is proportionately reduced by 23- 39% when compared to AFL and 48-60% when compared to WSE.

CONCLUSION

An efficient fault detection, localization and classification using Morlet Discrete Neuro Fuzzy Logic Wavelet Transform (MDFWT) on power transmission lines is presented. For fault detection, Morlet Envelope Spectrum (MES) was presented that efficiently detected the faults at the measured frequencies and time of the modulating components. For complex exponential carriers, the fault detection was performed on a multiplied Gaussian window and therefore handled the complex power circuit using the time frequency value. Discrete Wavelet Transform with Boltzmann Entropy theory was applied in MDFWT for efficient localization on power transmission lines that accurately located the position of the power fault on the power transmission line. Finally, an efficient classification of faults was observed using Neuro fuzzy logic wavelet transform with high reliability ratio. A comparative study of the proposed method with two other existing state of the art method shows that the modulated approach using time frequency component provides more fault localization accuracy. This was obtained by minimizing the fault detected error rate with improved system response time using a neuro fuzzy logic algorithm. The simulation results have been shown under different fault scenarios such as lower amplitude as Very Low (VL) fault, short duration as Medium Low (ML) fault, fast decaying as Medium High (MH) fault and high frequency current signals as Extremely High (EH) faults and so on. The obtained results indicate that the proposed fault detection, localization and classification using Morlet Discrete Neuro Fuzzy Logic Wavelet Transform significantly improves the capability of detecting fault types and of obtaining the exact fault location in power transmission lines with high reliability and stability.

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