H.V. Transmission Line Fault Location using Wavelet-based on ANN

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Abstract - The subject of estimating the fault location has been interesting to electric power engineers and utilities for a long time. The fault location algorithms are divided into two categories. The first is the algorithm based on impedance, while the second is based on the traveling wave. This work is based on these two categories to find the fault location by the time difference between the initial and its reflection arrival waves from the point of fault. The fault location using the traveling wave method proposed because it has good precision and is not affected by earth resistance, system parameters, serial capacitor, and line asymmetry. IN this work, the method developed by ANN to select the best mother wavelet. The best mother wavelet was selected and used to analyze the modal transformation of current signals. The single-ended method has been studied for several cases include different fault resistance, different fault position, and different model of a transmission line (traveling waves and multi-π section) and its Validation of the fault location performed using the MATLAB SIMULINK program. This method is verified by the current signals recorded at one end of a transmission line for the IEEE-9 bus system. The fault location technique was investigated in the laboratory simulated power station and transmission system model, the signal of a three-phase bus current was measured by transient option in powerpad instrument (Model 3945B), and using the national instrument data acquisition 16 analog input, 1.25 MHz sample/second.

***Key Words*: fault location, traveling waves, multi-π section, Single-ended method, wavelet transform, wavelet-based on ANN, etc….**

1. INTRODUCTION

Transmission lines are the connecting links between the generating stations and the distribution systems and led to other power system networks over interconnections. These lines are subjected to many kinds of faults; the principal types of fault are phase to earth, double phase to earth, phase-to-phase, and three phases. The maintenance engineer must fix and fined the fault location to restore the electrical power service as quickly as possible. Decrease the restoration time of the service will reduce the loss of revenue. Therefore, accurate "fault location "under a variety of fault conditions is an important issue.[1]

Faults in transmission lines that are caused by many objects such that insulation breakdown, lightning, freezing rainstorms, and snow, etc.[2]

The fault location problems were interested in many years by researchers and electrical power engineers. Most of the work up to date has been aimed to estimate the accurate transmission line faults location because of the impact of the H.V. transmission line.

The time required to investigate the transmission line faults on power systems is much larger than the faults in the distribution systems and sub-transmission lines.[3]

The distance relay was not accurate enough to detect the fault distance precisely about 15%, research efforts directed to develop dedicated fault location schemes by measuring the reactance from the sending end to the fault location. Brief coverage of the earliest methods for this purpose is presented in reference No.5 [4]. However, these simple and approximated methods also suffered from limited accuracy. Then the first generations of a traveling wave for the fault locators were introduced in the field in the 50s of the last century [5].

The basic idea of these schemes is based on determining the time for the injected wave to travel between the injection point and the fault position. Despite their remarkable performance as compared with reactance based ones at the time, they gradually abandoned due to the reliability and maintenance problems as well as to the economical factor [6]. Later, the great developments of injecting and capturing traveling wave signals as well as the modern algorithms support-traveling wave based on fault locators to represent strong competition to other fault location methods.

Many papers were then published employing this technique for fault location purposes. However, traveling wave-based schemes still suffer from different shortcomings and disadvantages [7]. Is another way introduced to capture and analyze the propagated transient waves based on voltages or currents during the fault.[5]

1.1 Transmission Line Fault Location Techniques

The methods for a transmission line fault location include:[8-9]

- Relating oscillographic readings to short–circuit study data. This method is slow requiring the oscillograms to receive and must be performed by individuals skilled in reading the oscillograms. It also depends on having short–circuit program data for the system configured, as it was when the fault occurred. It is very intolerant of fault resistance. Processing digital oscillograph record in a fault–locating program. This method is also slow. Large data records must receive by the computer, and then be processed by a person skilled in the operation of the program. Skills include selecting the proper voltage and current channels and selecting the data carefully from the faulted waveforms.

- Two–end traveling wave fault locators. These schemes measure the relative time of arrival of traveling wavefront produced by the fault, at the sending and receiving ends of the line. A high–speed (wide bandwidth) communications channel is required for accurate time measurement. Equipment at two ends of the line, as well as the communications channel, must be operating to obtain a measurement.

- One–end traveling–wave fault locators. A scheme developed for HVDC lines, which does not require equipment at both lines ends, and which needs no wide–bandwidth communications channel.

- One–end impedance–measuring fault locators. These devices calculate the fault location from the apparent impedance seen from the one end of the line. They have proved to be the most practical; since no communications channel is required, and they are generally easy to install. Commercial equipment based on analog techniques was not widely accepted, due to marginal performance. Several digital systems have been available for some time: these offer superior performance to the analog predecessors. Indeed, one end impedance-measuring fault locators are included in several digital distance relay packages, and the feature of fault locating adds little or nothing to the cost of the total system.

- Two end impedance fault locators. Given the voltage and current information at two ends of the line during a fault, the fault location can be calculated. The advantage of one such scheme is that ground faults can be set without knowing the transmission line zero-sequence impedance. The disadvantage of this scheme is similar to locating faults with digital oscillographs: must be the data retrieved and then processed by a relatively skilled individual. Although communications and computer resources could be applied to automate two–end schemes, the complexity and loss of availability (communications must be available) may seldom be worth the performance advantage. Indeed, the techniques discussed for handling sources of error in single–end fault locating bring the performance of single-ended schemes up to par with two–ended schemes in most cases.

1.2 Travelling Waves Method and Wavelet Transform Based on ANN

Traveling wave methods, like impedance methods, can be divided into one terminal (or single-ended) and two terminal (or double-ended). The one-end method is depending on the timing between reflections of voltage or/and current signals at impedance discontinuities. In this case, the aim is to find the distance between the sensors and the fault location while two-end methods are based on the time delay between arrivals information at the two ends of a transmission line.[6]

In overhead transmission line fault location traveling wave, methods are more accurate than impedance methods, it is providing accuracies in the range of (100–500) meter. [10]

Traveling waves–based overhead line fault locators classified by mode of operation; types A, B, C, D, and E [10-11-12-13].

The traveling wave fault location method uses only the information of the conductor length of the line (ℓ) and the propagation speed of the traveling wave (u) and the time difference between the arrival times of the traveling waves at each side of the line (tr–ts). The double-ended method or the time difference between the incident wave and the reflected traveling waves from the fault inception point at the single-end method. When comparing the traveling wave methods with the impedance methods, the first difference that can be observed is the absence of information of line parameters related to the nominal frequency, 60Hz or 50Hz, Table-1 shows a comparison of different algorithms for the same fault position.[14]

Table -1: Comparison between different algorithms for the same fault position

Algorithms	Station (1)		Station(2)	
	Km	Error	Km	Error
Real position	41.9	------	206.6	------
Travelling waves method	42.3	0.2%	206.2	0.2%
Single ended impedance method	31.5	4.2%	188.9	7.1%
Double ended impedance method	30.4	4.7%	218.2	4.7%

The study of electrical transient phenomena in the power system involves a frequency range from DC to about

50 MHz or in specific cases even more. Above power frequency, these usually involve electromagnetic phenomena, whereas below power frequency also transients of the electro-mechanical type in rotating machines can be involved.

Table-2 gives an overview of the various origins of transients and their most common frequency ranges. Minimum frequency values below power frequency indicate the frequency band required to represent the main time constants of the relevant transients.[10]

The wavelet multiresolution analysis is a suitable and powerful method of signal analysis and it is well especially to traveling wave signals.[15]

Table-2 Origin of electrical transients and associated frequency ranges.

Origin	Frequency Range
Transformer energization & Ferroresonance	(DC),(AC) 0.1Hz-1Hz
Load rejection	0.1Hz-3KHz
Fault clearing	50Hz-3KHz
Fault initiation	(DC),(AC) 50Hz-20KHz
Line energization	50Hz-20KHz
Line reclosing	(DC),(AC) 50Hz-20KHz
Transient recovery voltage 1-Terminal faults 2-Short line faults	 50Hz-20KHz 50Hz-100KHz
Multiple restrikes of circuit breaker	10KHz-1MHz
Lightning surges & Faults in substations	10KHz-1MHz
Disconnected switching & Faults in GIS	100KHz-50MHz

Wavelets can support multiple resolutions in both frequency and time domains. The wavelet transforms scanning window is using the short time intervals for the high-frequency and long time intervals for the low-frequency. Wavelet analysis is based on the decomposition 'details' of a signal into scales using a specific wavelet analyzing function called mother wavelet.

Wavelet has a digital implementation called the discrete wavelet transform (DWT). The generated waveforms were analyzed with multiresolution wavelet analysis to extract the sub-band of frequencies information from the simulated transients signal. Daubechies wavelets are commonly used in the analysis of traveling waves.

The match closely to find the processed signal, which is very important in wavelet applications. Daubechies wavelets are more localized i.e., compactly supported in time and hence are good for fast and short transient analysis. However, some mother wavelets show a good engagement with the transient analysis signals and may use in a different transient analysis condition. Several wavelets have been used in this work. ANN presents the comparison to get the minimum error between the original signal and the decomposition signal of the multi-mother wavelet.

Where the mother wavelet comparison depicted in ANN are Daubechies wavelets: (db2, 4, 6, 8, 10, 15, 20, and 30), Symlets (sym4, 6, 8, and 10). Coiflets (coif1, 2, 3, 4 and 5), and Biorthogonal wavelets: (bior1.1, 1.3, 1.5, 2.2, 2.4, 2.6, 2.8, 3.1, 3.3, 3.5, 3.7, 3.9, 4.4, 5.5 and 6.8).

The Daubechies wavelets show a good correlation with the fault signal. This is investigation can be performed each time the fault location algorithm is carried out.

2. Power system modeling

The proposed fault location estimation approach was extensively tested on a 9-buse IEEE. The system is shown in Fig-1 had been simulated by using the Matlab toolbox and ETAP (Electromagnetic Transient Alternative Program) program. The Flow chart of the proposed method as shown in Fig-2.

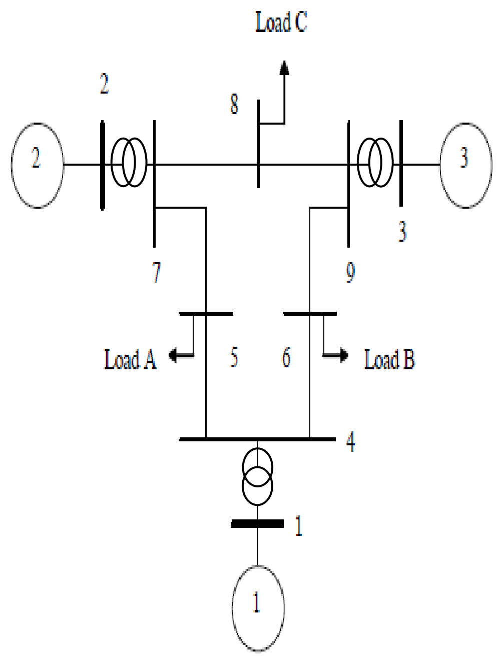

Fig -1: IEEE – 9 bus system

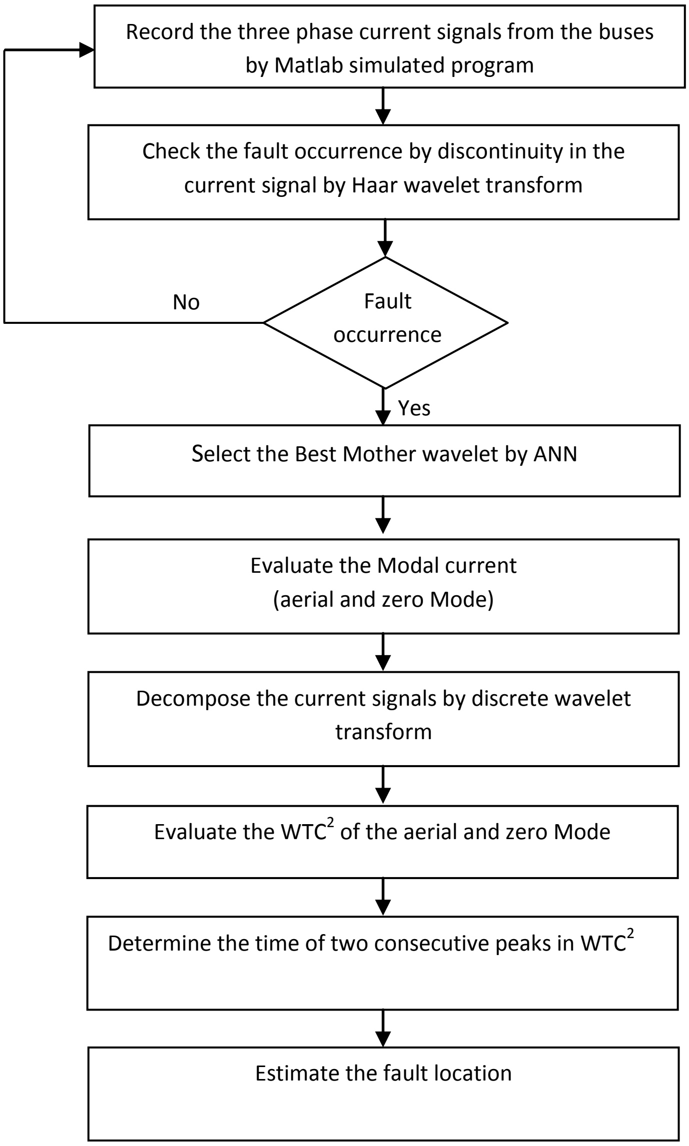

Fig -2: The Flow chart of proposed method

The simulation performed with two different line models:-

- (π) Sections line.
- Distributed parameters (based on traveling waves) line.

In transient studies with (π) sections, it is important to consider whether one section or several sections should represent a line. This is dependent upon the following:

- The traveling time (τ).
- The frequency of response required from the simulation model.
- The length of the line (ℓ).

A good approximation of the maximum frequency range represented by the (π) line model given by the following equation [16]:

$$f_{\max} = \frac{\text{number of } \pi \text{ section} * u}{8\ell}$$

Where: u propagation velocity.

ℓ the total length of the transmission line.

For a 321.8Km line having a propagation speed of 293928.617 Km/s (97.97% of the speed of the light), the maximum frequency range represented with a single (π) section is approximately 114Hz, for a switching surge (or fault) studies involving high-frequency transients in the kHz range, much shorter (π) sections should be used.

By using the equation, the number of (π) sections in the transmission line ℓ96 of the IEEE-9 bus system can thus estimate. If the fmax. is 20 kHz and the speed of the wave is 293928.617(Km/s) then the number of π section

$$= \frac{20000(Hz)*8*321.8(Km)}{293928.617(Km/s)}$$

=175 (sections)

The Matlab-Simulink based multi-(π) section simulation model of the IEEE -9 bus system is as shown in Fig-3.

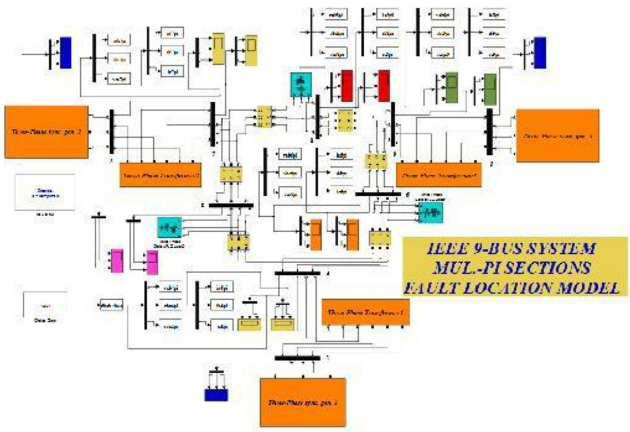

Fig -3 Multi-(π) section IEEE-9 bus Model

The distributed parameters transmission line model operates on the principle of traveling waves. The signals of Voltage and current are disturbances that will travel along a conductor line at its velocity of propagation until it is reflected at the end of the line. In a sense, the transmission on an overhead line or a cable is a delay function. The calculated step time (Δt) of the simulation should be less than the propagation time (τ). The distributed parameter model is based on Bergeron's traveling wave method. Bergeron's method based on the LC distributed parameters traveling wave line model with lumped resistance.

The Matlab-Simulink is based on the traveling wave model (Bergeron's model) simulation of the IEEE -9 bus system as shown in Fig-3.

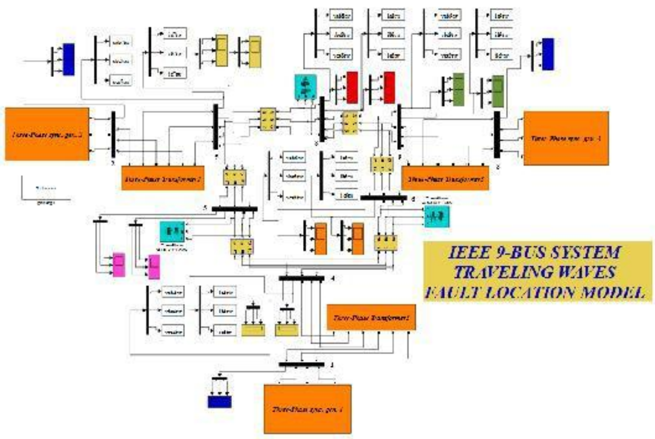

Fig -3 Travelling waves model of the IEEE-9 bus system

The IEEE -9 bus system given in simulated for both of the multi-(π) section and traveling wave's models as shown (Fig-2 & Fig-3) to generate the required data, which is used to estimate the fault location.

Different types of faults, fault resistance, and fault position simulated and the currents and voltages recorded in data fields for each case of simulation. The simulation fault cases of the traveling waves and multi-(π) section model listed in Table-3.

Table-2 the simulation fault cases of the traveling waves and multi-(π) section model.

No. of fault position	Fault resistance Rf=0.001 Ω		Rf=0 Ω	Fault resistance Rf=1 Ω		Rf=0 Ω	Fault resistance Rf=10 Ω	
	abc	ag	ab	abc	ag	ab	abc	ag
Position 1	* ^	* ^	* ^	* ^	* ^	* ^	* ^	* ^
Position 2	* ^	* ^	* ^	* ^	* ^	* ^	* ^	* ^

Where:
abc: three-phase to ground fault.
ag: single phase to ground fault.
ab: phase-to-phase fault.

* -Multi-(π) section model.

^-Travelling wave model.

3. Simulation and Practical Results

The simulations were carried out by using the Matlab Simulink program. The results were processed using the Wavelet Analysis Toolbox. The sampling frequency is chosen as 1MHz (i.e. sampling time 1μsec.) for the traveling wave model and 20 kHz (i.e. sampling time 50μsec.) for Multi-(π) section model.

3.1 Results of Travelling Wave Model

The ground and aerial mode of WTC^2 (Wavelet Transform Coefficient Square) for a three-phase to ground faults located at 80.45km from the bus (6) (position 1) for Rf =0.001Ω, 1Ω and 10Ω are shown in Fig-(4, 5, 6, 7, 8 and 9) respectively. The first scale signal obtained for aerial and ground modes calculated at their DWT. The algorithm classifies the fault as grounded because the WTC^2 of the ground mode is significant. The time difference between these two signals is less than the time difference produced by a fault located in the middle of the line. Hence, the fault is in the first half of the line concerning bus (6) (close-in faults). The aerial mode signal is computing by the time difference between the two sequential peaks. The fault location can be calculated as:

$$FL = \frac{293928.617*(2000686-2000139)*1*10^{-6}}{2} = 80.389 \text{ km}$$

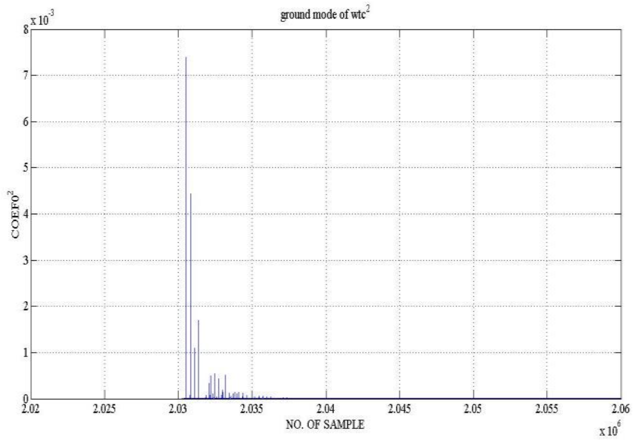

Fig-4 The ground mode of WTC^2 at R_f=0.001

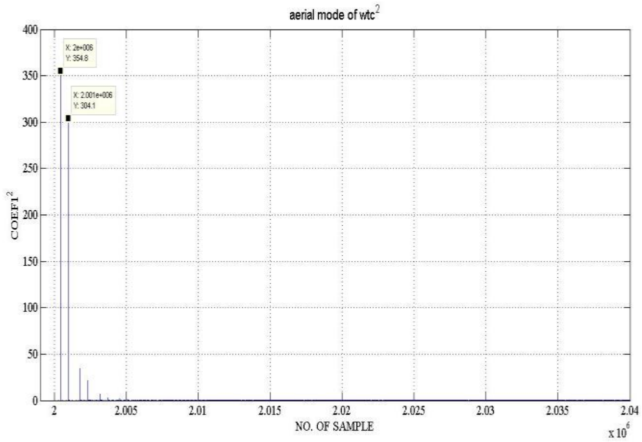

Fig-5 The aerial mode of WTC^2 at Rf=0.001

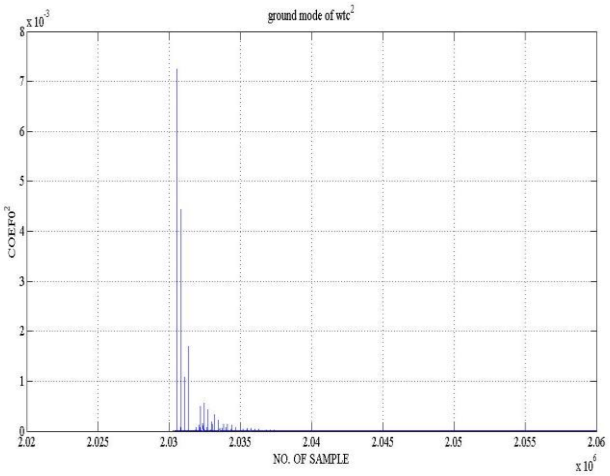

Fig-6 The ground mode WTC^2 at Rf=1

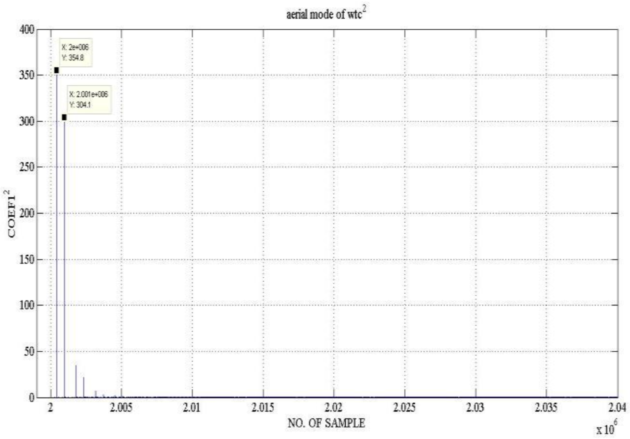

Fig-7 The aerial mode WTC^2 at Rf=1Ω

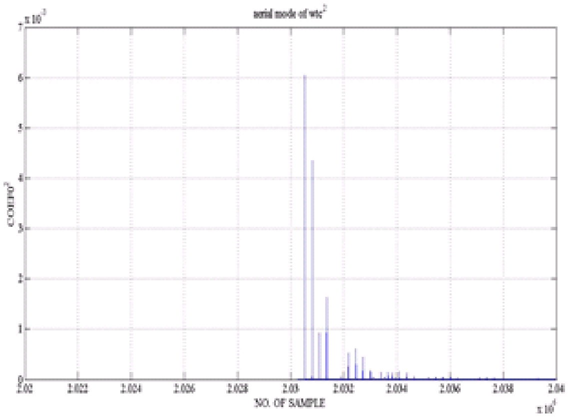

Fig-8 The ground mode WTC^2 at Rf=10Ω

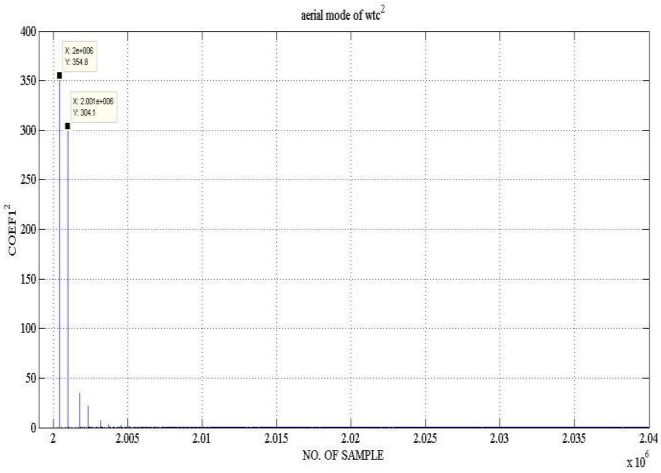

Fig-9 The aerial mode WTC^2 at Rf=10Ω

If the same method is applied to find the location of the fault, in the two cases of the phase-to-ground fault and phase-to-phase fault, we will find that the calculated value in the first case is the same for those two cases and the error rate will be the same as well.

In the same procedures, we can find the ground and aerial mode of WTC^2 for a three-phase to ground fault located at 241.35Km (position 2) remote-end faults from the bus (6) for Rf =0.001Ω, 1Ω, and 10Ω, Fig-(10, 11, 12, 13, 14, and 15) shows the ground and aerial mode of WTC^2 for this case respectively.

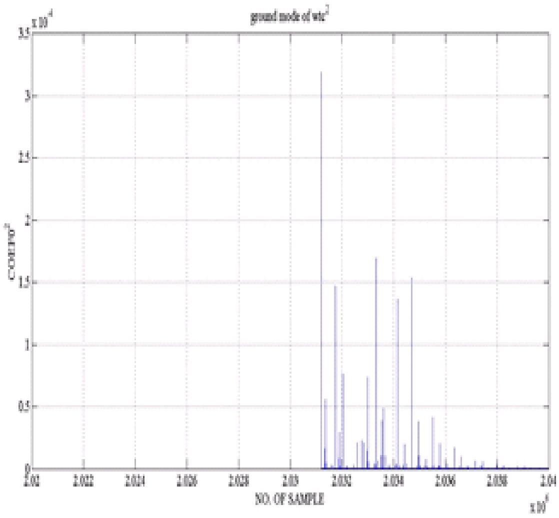

Fig-10 The ground mode WTC^2 at Rf=0.001Ω

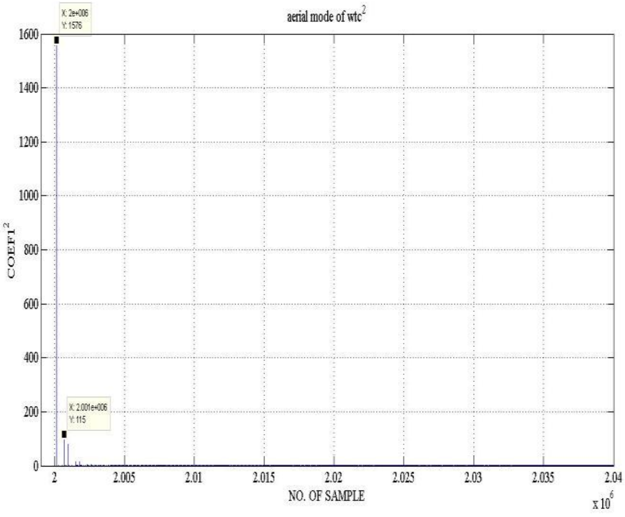

Fig-11 The aerial mode WTC^2 at Rf=0.001Ω

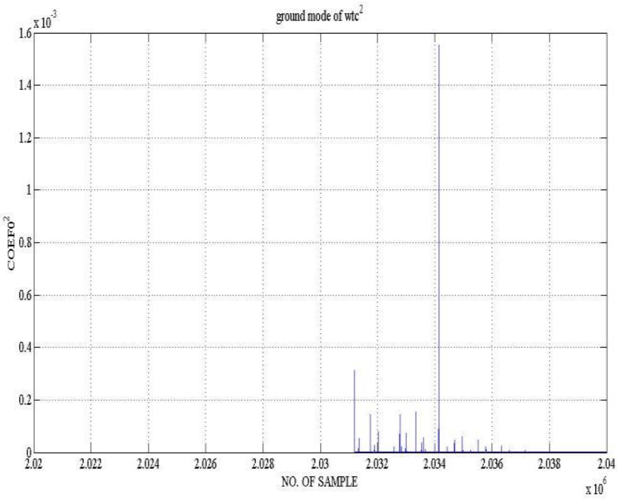

Fig-12 The ground mode WTC^2 at Rf=1Ω

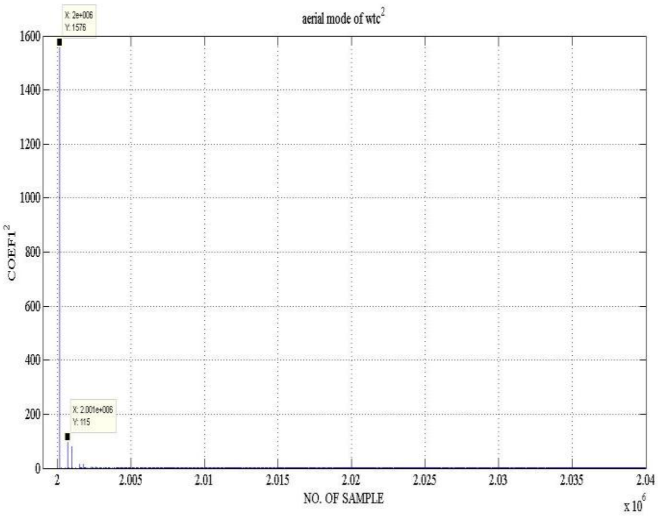

Fig-13 The aerial mode WTC^2 at Rf=1Ω

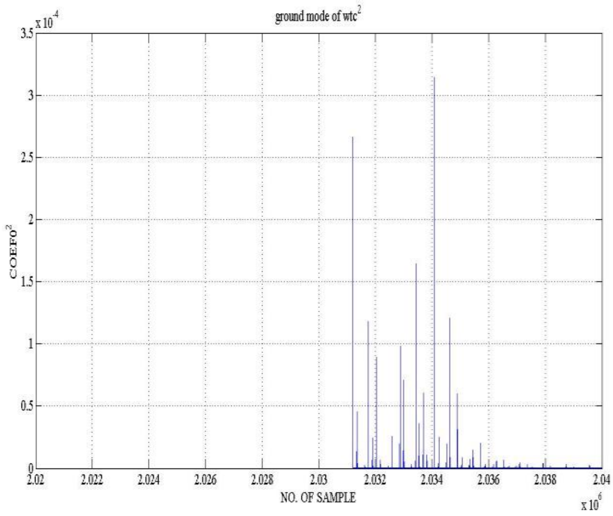

Fig-14 The ground mode WTC^2 at Rf=10Ω

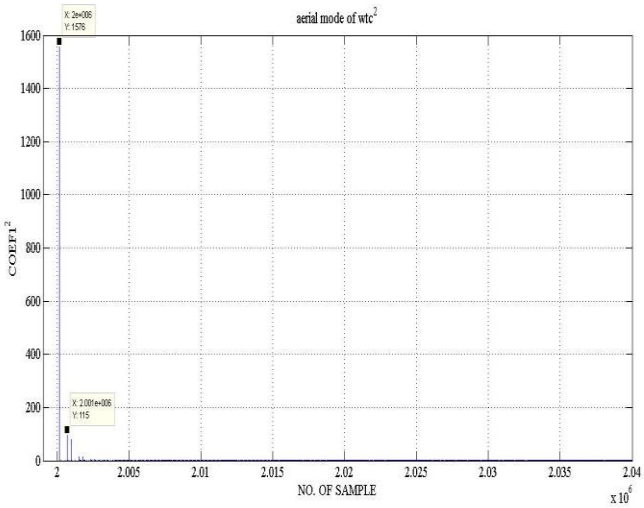

Fig-15 The aerial mode WTC^2 at Rf=10Ω

The ground mode WTC^2 would be signed by the time difference between these two signals is greater than the time difference produced by a fault located at the center of the line.

The algorithm would therefore classify the fault as grounded and located on the remote half of the transmission line concerning bus (6).

In this case, the fault location FL is given by:

$$FL = \ell - \frac{u \cdot (t_2 - t_1)}{2}$$

Where:

- ℓ is the line length (km).
- (t2-t1) is the time difference between two consecutive peaks of the maximum value of WTC2 of the aerial mode (sec.).

Now the fault location can be calculated from the aerial mode:-

$$=321.8-\frac{293928.617*(2000960-2000413)*1*10^{-6}}{2}$$

= 241.41 Km

If the same method is applied to find the location of the fault, in the two cases of the phase-to-ground fault and phase-to-phase fault, we will find that the calculated value in the second case is the same for those two cases and the error rate will be the same as well.

The Matlab Simulink program simulated several fault types, fault locations, fault resistance, and system modeled by a traveling wave. The performance of the fault location techniques, therefore, verified using a set of cases whose results were reported and discussed. The error of the fault location calculated as follows:-

error%= $\frac{\text{Actual fault location-Calculated fault location}}{\text{The total length of the transmission line}}$ *100

The error, in this case, appear to be

$$error\%=\frac{80.45-80.389}{321.8}*100$$

= 0.0188 %

3.2 Results of Multi (π) section Model

The single-ended fault location algorithm is applied to the IEEE-9 bus system simulated by the multi (π) section model is shown in Fig-3. The results of the ground and aerial mode at the three-phase to ground fault located at 80.45 km from the bus (6) shown in Fig-16 and Fig-17.

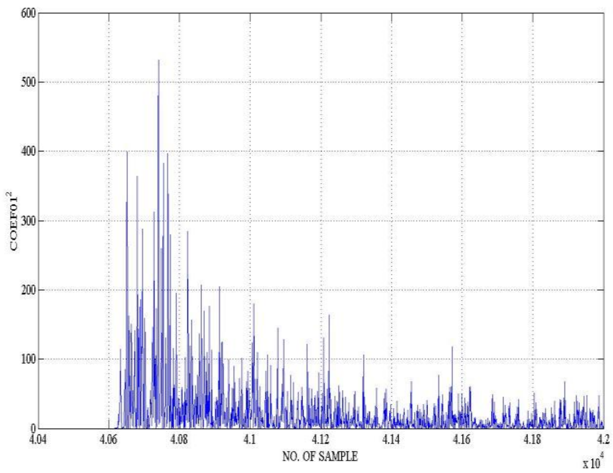

Fig-16 The ground mode WTC^2 at Rf=0.001Ω

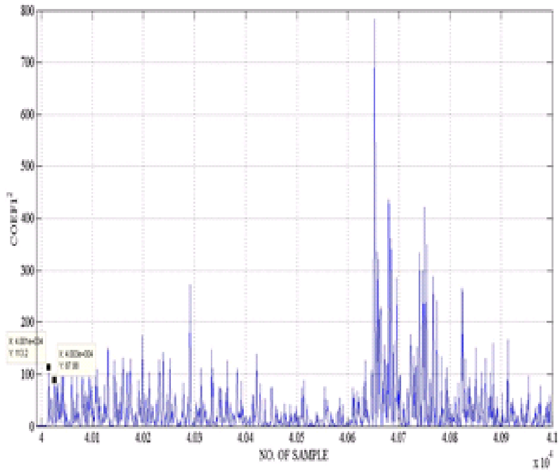

Fig-17 The aerial mode WTC^2 at Rf=0.001Ω

The fault location estimated in this case can be calculated as:

$$FL=\frac{u\cdot\Delta t}{2}$$

$$FL=\frac{293928.617*(40026-40014)*50*10^{-6}}{2}$$

= 88.178 km

The error, in this case, appear to be

$$error\%=\left|\frac{80.45-88.178}{321.8}\right|*100$$

= 2.4 %

3.3 Fault Location Method Investigation of 220kV practical Transmission Line

Traveling wave current measurements have been collected from the power system transmission line network laboratory. Bus names as shown in the single line diagram of the 220-kV network in Fig-18 and the system rating and parameters listed in appendix (C). A real-time fault current measured at the generator bus (A) with different fault types (abc to ground, a to ground, and ab) were recorded at different positions (100 km "bus(B)" and 200 km "bus(C)") from this bus.

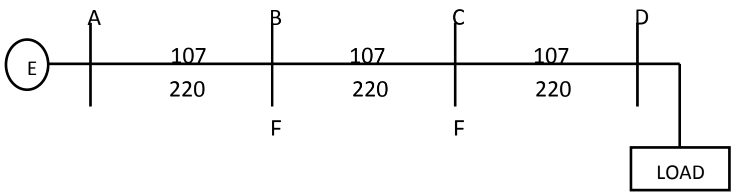

Fig-18 The single line diagram of 220-kv practical

The results of fault current obtained by powerpad instrument and National instrument Data acquisition respectively to analyzed using the single-end method and the aerial and ground mode signals, and the DWT coefficient squared to estimate the fault location.

3.3.1 Powerpad Instrument

The current signals have been analyzed by the proposed technique and the fault location was estimated by the same procedure illustrated in the section (2.1 and 2.2).Fig-(19 and 20) shows the WTC² of the ground and aerial mode for a three-phase to ground fault respectively.

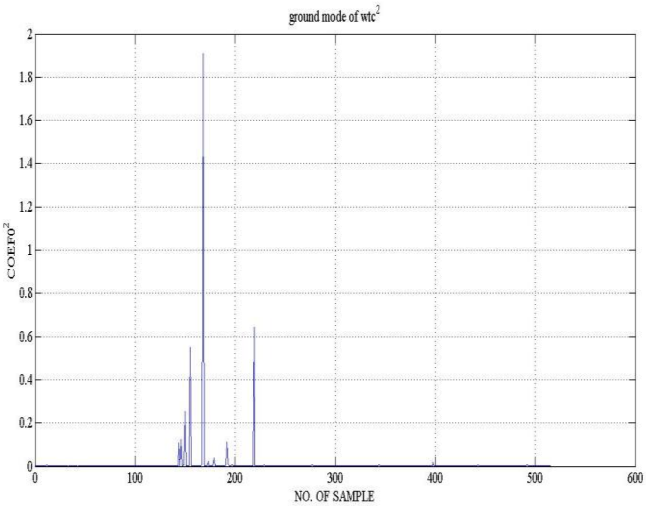

Fig-19 The ground mode WTC²

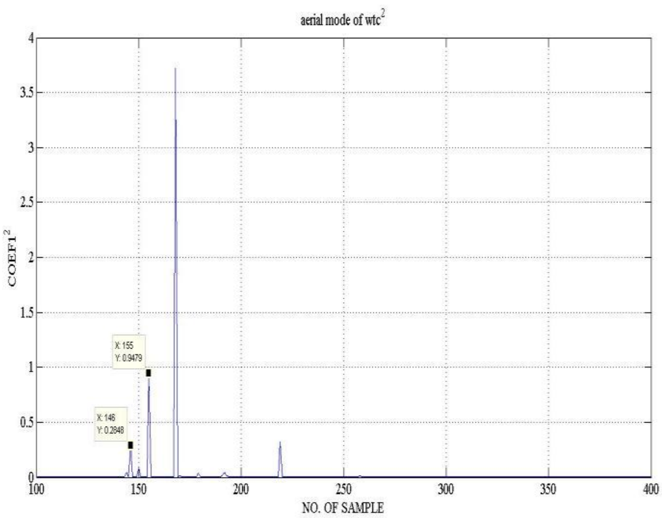

Fig-20 The aerial mode WTC²

The fault located at 107 km in the transmission line (107 km from the generation bus) can be calculated by:

$$FL = \frac{u \cdot \Delta t}{2}$$

$$FL = \frac{295408.9752*(155-146)*80*10^{-6}}{2}$$

= 106.347 km

Also, the percentage of error is

$$error\% = \frac{107-106.347}{100}*100$$

= 0.65 %

Where u is the velocity of the traveling wave in the practical model and it is equal to (295408.9752 km/sec).

Fig-(21 and 22) shows the WTC2 of the ground and aerial mode for a single-phase to ground fault respectively.

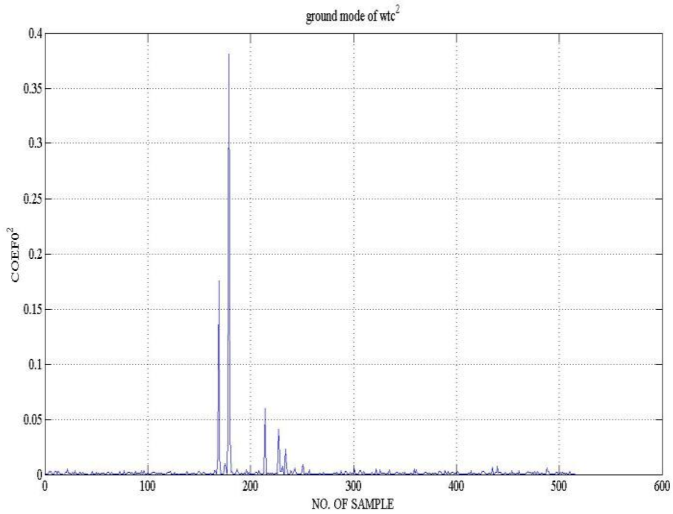

Fig-21 The ground mode WTC²

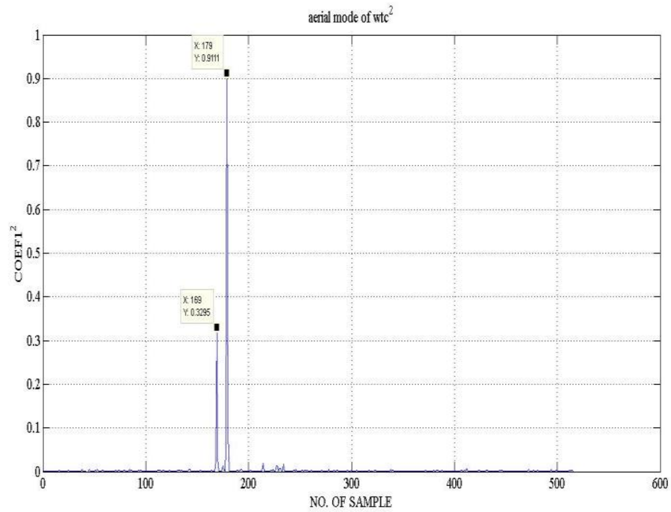

Fig-22 The aerial mode WTC²

Fig-(23 and 24) shows the WTC² of the ground and aerial mode for a phase-to-phase fault respectively.

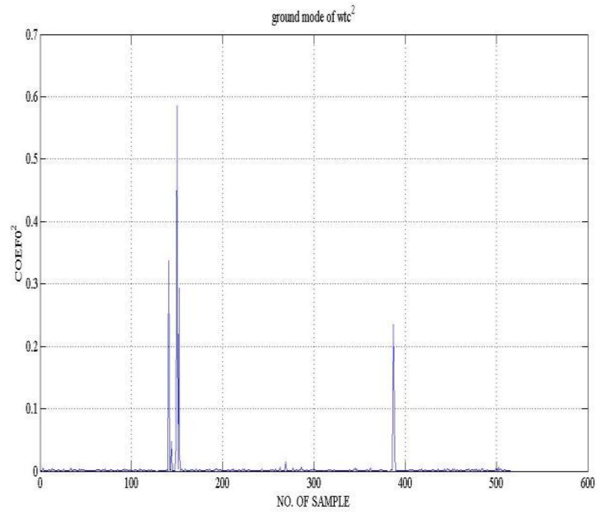

Fig-23 The ground mode WTC^2

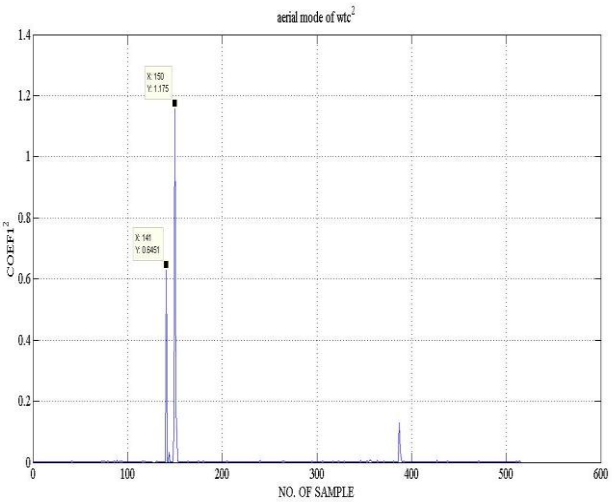

Fig-24 The aerial mode WTC^2

3.3.2 National Instrument Data Acquisition

The current signals have been analyzed by the proposed technique and the fault location estimated by the same procedure illustrated in the section (2.1 and 2.2). Fig-25 shows the WTC^2 of the aerial mode.

From the results shown in Fig-25, it is to be noted that the Data Acquisition instrument is not able to provide significant details to evaluate the fault location, because the current transformer used in measurements has a small frequency range (DC to 5 kHz), and thus reaching to saturation region.

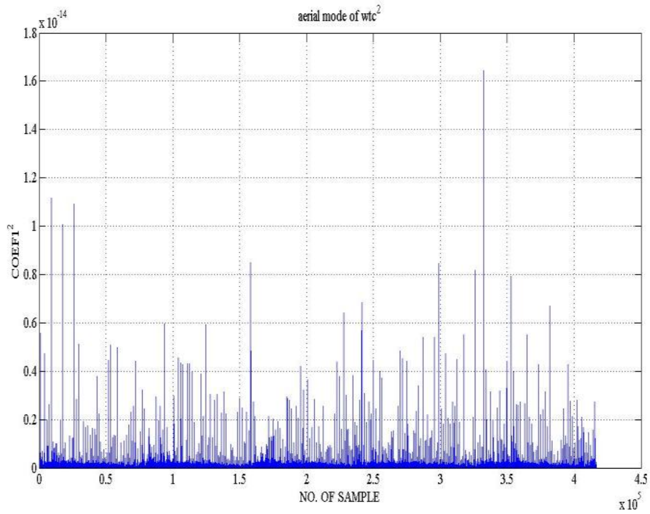

Fig-25 The aerial mode WTC^2

4. CONCLUSIONS

All the simulations are repeated and replacing the fault resistance Rf by 0.001, 1, and 10Ω. In this case, it is observed that the wavelet coefficients square of the initial peaks aerial mode are smaller than those obtained by using on zero fault resistance are; depending on the resistance value, however, the shape and peak arrival instants of the waveforms remain the same. The fault location results obtained with Rf = 0.001Ω, are closely matched with those obtained by using Rf = 10Ω. Based on this limited set of experimental results, it is seen that the algorithm performance will remain insensitive to variations in the fault resistance. The traveling wave fault location technique provides accurate fault location solutions for the transmission line. The distance to fault error measurement in the simulation model is (0.0188%), and (0.65%) for a practical result. The traveling wave technique is free from the influences of the factors, which affect fault location accuracy of traditional impedance measurement methods. These factors are Fault resistance, Voltage and Current transformer error, Insufficient accuracy of line parameters due to neglecting of line transposing, distributed capacitance, etc., Uncertainty of zero sequence impedance due to variation of earth resistivity along the transmission line path, and independent of the direct current flow.

The traveling wave fault location is more dominant as compared with impedance measurements methods since it can be used to measure the distance to fault in all kinds of power lines, including, AC transmission lines, HVDC transmission lines, seriously compensated transmission line, Line with T branches, and the line containing cable sections and overhead line.

A simple (π) section model cannot give the correct results at higher frequencies (error = 2.4%); it is suitable for very short lines where the traveling wave models cannot be used. The (π) section models are generally not the best choice for transient solutions, because traveling wave solutions are faster and usually more accurate.

The fault location error is related to the sampling time were used in recording the fault transient signals.

For grounded faults near the middle of the line, mode (zero) signals from the fault and the far end become comparable increasing the error of the fault location algorithm.

The solution of the single-ended problem for faults at the close-in or remote fault point from one bus can be mitigated using the energy of the DWT coefficients. The energy has a lower value for a fault at the remote end of the line than those at the close-in end of the line. Therefore, the energy method has been used in this work to discriminate between close-in and remote-end faults.

REFERENCES

[1] Zhang Qingchao; Zhang Yao; Song Wennan; Yu Yixin; Wang Zhigang, "Fault location of two-parallel transmission line for non-earth fault using one-terminal data," Power Engineering Society 1999 Winter Meeting, IEEE, vol.2, no., pp. 967 vol.2, 31 Jan-4 Feb 1999.

[2] M.M. Saha, J. Izykowski, E. Rosolowski, "Fault Location on Power Networks", Springer-Verlag London Limited 2010.

[3] A New Technique for Location of Fault Location on Transmission Lines by Khalaf Y. Alzyoud, Al-Mofleh Anwar, Faisal Y. Alzyoud, Modern Applied Science, Vol. 4, No. 8, August 2010.

[4] Kezunovic, M., "Intelligent systems in protection engineering,". International Conference on Power System Technology, pp.801-806 vol.2, 2000.

[5] Lewis, Laurel J., "Traveling Wave Relations Applicable to Power-System Fault Locators," American Institute of Electrical Engineers, Transactions of the vol.70, no.2, pp.1671-1680, July 1951.

[6] Sneddom, M.; Gale, P., "Fault location on transmission lines," Distribution and Transmission Systems (Digest No. 1997/050), IEE Colloquium on Operational Monitoring, vol., no., pp.2/1-2/3, 28 Jan 1997.

[7] M.SC., Kurt Josef Ferreira, "Fault Location for Power Transmission Systems Using Magnetic Field Sensing Coils". Degree of Master of Science in Electrical and Computer Engineering, April 2007.

[8] Edmund O. "a review of impedance-based fault locating experience", October 16, 1990, Omaha, Nebraska.

[9] A. S. Maner and S. Lavand, "Accurate Fault Location Estimation of High Voltage Transmission Line Using Disturbance Record," 2018 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), Chennai, 2018, pp. 26-30, DOI: 10.1109/ICPECTS.2018.8521637.

[10] IEEE Guide for determining fault location on AC transmission and distribution lines, 2005. Power System Relaying Committee http://www.pes-psrc.org/.

[11] Lou Van der sluis "Transients in power systems", John Wiley and Sons Ltd, 2001.

[12] H. Liao, Y. Yuan, L. Liu, and P. Yu, "Traveling Wave Fault Location Method Analysis and Prospect," 2020 5th Asia Conference on Power and Electrical Engineering (ACPEE), Chengdu, China, 2020, pp. 1419-1423, DOI: 10.1109/ACPEE48638.2020.9136332.

[13] Crossley, P.; Davidson, M.; Gale, P., "Fault location using traveling waves," Instrumentation in the Electrical Supply Industry, IEE Colloquium on, vol., no., pp.6/1-6/3, 29 Jun 1993.

[14] Zimath, S. L.; Ramos, M. A. F.; Filho, J. E. S., "Comparison of impedance and traveling wave fault location using real faults," Transmission and Distribution Conference and Exposition, 2010 IEEE PES, vol., no., pp.1-5, 19-22 April 2010.

[15] Raj Aggarwal, "Wavelet transforms in power systems. I. General introduction to the wavelet transforms," Power Engineering Journal, vol.14, no.2, pp.81-87, April 2000.

[16] B. Mork, R. Nelson, B. Kirkendall, N. Stenvig, "Determination of High-Frequency Current Distribution Using EMTP-Based Transmission Line Models with Resulting Radiated Electromagnetic Fields", IEEE International Symposium on Power Line Communications and its Applications Rio de Janeiro, Brazil March 28, 2010, through March 31, 2010