FFT Based Fault Location Algorithm for Transmission Lines

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Abstract

To maintain continuity of electrical energy, fast clearance of a fault is needed, which requires accurate determination of the fault location on transmission lines. This paper proposes a method for fault location, which is based on time to frequency domain transformation of measured data after fault by using Fast Fourier Transform (FFT). The frequency of the first harmonic is utilized for determination of the fault location using travelling wave theory. The results show that the accuracy of the method is not affected by the fault resistance and phase angle of fault instant.

1. Introduction

Reliability and continuity of electrical energy has gained more importance in last decades as power outages lead to loss of manpower and resources in industrial plants. The most important causes of disturbances in the power systems are unexpected faults, and short circuit faults are more common fault types, which are arisen due to lightning surges, usage of defective materials, improper operation, human errors, overloading and aging, and may cause loss of system stability, failure of transformers, generators and transmission lines. Fast clearing of faults is greatly significant and the first step for removing a fault in a short time is to estimate the fault location quickly and accurately.

Advance in the computer technology allows development of new algorithms for determination of fault location and in recent years several methods have been proposed for identification of the fault location in power systems. The studies for determination of fault location may be classified into two categories; the methods which employ post-fault steady-state voltage and current phasors and the methods based on the transient wave theory. In some of the methods which power frequency phasors have been used fault distance is estimated from the information received from one end of the transmission line [1-6]. As fault location is estimated by impedance from measuring terminal to the fault point, unknown fault impedance affects the accuracy. To overcome this difficulty, two- or multi-ended fault location techniques have been used [7-11]. However, measurement from two end is difficult and synchronized sampling of the voltage and current data from two ends of the line is usually required. In the travelling wave based methods on the other hand, time-space analysis have been used for fault location. Short and open circuit faults on transmission lines cause sudden changes in the distribution of electric and magnetic energy which result travelling waves. In order to determine the fault distance, the analysis of wave time-position graphs are needed [12-17]. In recent years, many studies have been devoted to develop different methods based on the wavelet transform to determine the fault type and location of faults [14-17]. Wavelet transform is a recently developed mathematical tool, which is used to capture the dynamic characteristics of unstable signals using short data windows. Depending on the direction in the protection of transmission lines, fault classification and fault distance identification using wavelet transform was carried out by separating the necessary information from the short circuit transient behavior. The most important limitation of the existing methods based on the wavelet transformation is the low degree of accuracy in the prediction faults points near the busbar in general.

In this study, a new method based on FFT for determination of fault location using frequency domain data obtained by transformation of transient response measured on one terminal of transmission line is proposed. Short circuit current and voltage waveforms obtained by computer simulations are evaluated, and algorithms will be applied to transient current and voltage waves in one or two periods as inputs, fault location is determined.

The organization of the paper is as follows: After this introductory section the state-space techniques are presented for transient voltage and current waveforms of faulty transmission line in Section 2. In the 3th section the theory of fault distance calculation using travelling wave theory of the distributed parameter transmission line is introduced. In Section 4 application results are summarized; the effect of fault resistance, the affect of phase angle and the effect of source inductance is investigated.

2. State-Space Modeling of Transmission Line with Short Circuit Fault

Computer programs such as ATP or MicroTran are available for transient analysis of transmission lines. However, many simulations are needed for several cases and transformation of numerical data into Matlab environment is difficult. To overcome this difficulty, state-space method is used to analyze transmission line with short circuit fault.

State equation of a linear time invariant system are written as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\,\mathbf{u}(t) \quad (1)$$

Where $\mathbf{x}$(t) is state vector, $\mathbf{A}$ and $\mathbf{B}$ are coefficient matrices with proper dimensions and $\mathbf{u}$(t) is vector of inputs.

The transmission line shown in Fig. 1 is simulated by series connection of lumped parameter L-sections and a single phase to ground short circuit at a point on transmission line with zero fault resistance is simulated by removing the conductance and capacitance at the specified node on lumped parameter model and v_k becomes zero and it is not a state variable at all. Then the matrices $\mathbf{x}$, $\mathbf{A}$, and $\mathbf{B}$ can be written as follows:

$$\mathbf{x} = \begin{bmatrix} i_1 & v_1 & i_2 & \cdots & v_{k-1} & i_k & i_{k+1} & v_{k+1} & \cdots & i_n & v_n \end{bmatrix}^T \quad (2)$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_1 & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_1 \end{bmatrix} \quad (3)$$

$$\mathbf{B} = \begin{bmatrix} \dfrac{1}{L_1} & \mathbf{0} & \ldots\ldots & \mathbf{0} \end{bmatrix}^T \quad (4)$$

where

$$\mathbf{A}_1 = \begin{bmatrix} -R_1/L_1 & -1/L_1 & & & & & 0 \\ 1/C & \text{-G/C} & \text{-1/C} & & & & \\ & \text{1/L} & \text{-R/L} & -1/L & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & & 1/C & -G/C & \text{-1/C} \\ 0 & & & & & 1/L & -R/L \end{bmatrix}$$

$$\mathbf{A}_2 = \begin{bmatrix} -R/L & -1/L & & & & 0 \\ 1/C & -G/C & 1/C & & & \\ & \ddots & \ddots & \ddots & & \\ & & 1/L & -R/L & -1/L & \\ 0 & & & 1/C & -G/C & \text{-1}/C \end{bmatrix}$$

R, L, C and G are parameters of transmission line per section. In (4), $L_1=L_s+L$ and $R_1=R_s+R$ where R_s and L_s are source resistance and inductance respectively. If fault resistance is different than zero, state vector and coefficient matrices are:

$$\mathbf{x} = \begin{bmatrix} i_1 & v_1 & i_2 & \cdots & v_{k-1} & i_k & i_{k+1} & v_{k+1} & \cdots & i_n & v_n \end{bmatrix}^T \quad (5)$$

$$\mathbf{A} = \begin{bmatrix} -R_1/L_1 & -1/L & 0 & \ldots & 0 \\ 1/C & -G/C & -1/C & & \\ \vdots & \ddots & \ddots & \ddots & \\ & & 1/L & -R/L & -1/L \\ 0 & \ldots & 0 & 1/C & -G/C \end{bmatrix} \quad (6)$$

with $a_{kk} = -(G + \dfrac{1}{R_f})/C$, where R_f is fault resistance, and

$$\mathbf{B} = \begin{bmatrix} \dfrac{1}{L_1} & \mathbf{0} & \ldots\ldots & \mathbf{0} \end{bmatrix}^T . \quad (7)$$

Analytic solution is preferred in this study and direct solution in time domain is obtained from the solution of Eq. (1) for a sinusoidal excitation as:

$$\mathbf{x}(t) = \mathrm{Re}\left\{ e^{\mathbf{A}(t-t_0)}\mathbf{x}_o + (p\mathbf{I} - \mathbf{A})^{-1}(e^{pt}\mathbf{B}U - e^{\mathbf{A}(t-t_0)}\mathbf{B}Ue^{pt_0}) \right\} \quad (8)$$

where U is the peak value of the sinusoidal excitation and $p=\sigma+j\omega$. This equation gives the complete response of the system. Detail about computing *x(t)* can be found in [18,19].

3. Theory of Fault Distance Calculation

Voltage and current phasors $\mathbf{V}$ and $\mathbf{I}$ at any point on the line with series impedance $\mathbf{z} = r + jwl$ and shunt admittance $\mathbf{y} = g + jwc$ are determined as [20]

$$\mathbf{V} = C_1 e^{\gamma x} + C_2 e^{-\gamma x} \quad (9)$$

$$\mathbf{I} = \frac{1}{z_0} C_1 e^{\gamma x} - \frac{1}{z_0} C_2 e^{-\gamma x} \quad (10)$$

The constants C_1 and C_2 can be evaluated by using the conditions at terminals of transmission line. Propagation constant of a transmission line is $\gamma = \sqrt{zy} = \alpha + j\beta$, where attenuation constant α measured nepers per unit length and phase constant β radians per unit length. A wavelength λ is the distance along a line between two points of a wave which differ in phase by 360^0, or 2π rad. If β is the phase shift in radians per mile, the wavelength in km is

$$\lambda = \frac{2\pi}{\beta} \quad (11)$$

The velocity of propagation of a wave in km per second is

$$v = f\,\lambda \quad (12)$$

where f is frequency in Hertz and λ is wavelength in km. The velocity of propagation in terms of line parameters can be approximately obtained as

$$v = 1/\sqrt{lc} \quad (13)$$

Let τ_f is travel time from fault point to measuring point which is theoretically calculated as

$$\tau_f = x/v \quad (14)$$

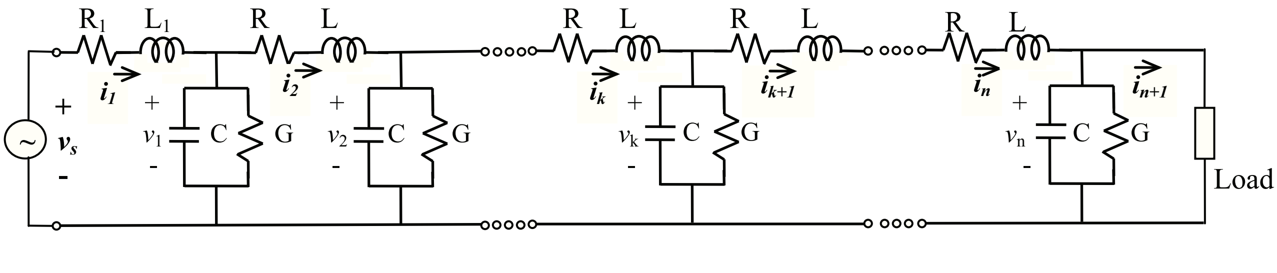


Fig. 1. Lumped parameter equivalent of the transmission line

It has been observed form the simulation results that the frequency of harmonics generated after the fault are proportional to travel time as

$$f_1 = \frac{1}{2\tau_f}, \quad f_2 = \frac{1}{\tau_f}, \quad \ldots \quad f_i = \frac{i}{2\tau_f} \tag{15}$$

Hence, if the wave speed and frequency of i^{th} harmonic f_i is known, fault distance can be found from the following equation:

$$x = v\tau_f = iv/2f_i \tag{16}$$

With the help of signal processing techniques voltage and current harmonics, which occurs as a result of short circuit, can be subtracted from measured voltage and current signals. These harmonics of the voltage signal can be obtained by using FFT.

4. Applications and Results

As an application, a 231 kV, 350 km single-phase line with parameters r=0.02 Ω/km, l=0.88 mH/km and c=13 nF/km is considered. Source resistance is assumed to be 0.01 Ω and source inductance is 1.0 mH. Surge velocity on the line is $v=(lc)^{1/2}$=295.66x10^3 km/s. Transient voltage and current waveforms after fault are obtained using state-space techniques. Time to frequency domain conversion is carried out using FFT. For this, one period (20 ms) of the voltage and current signals is sampled at 102.4 kHz, and for 20 ms sampling time the FFT spectrum resolution is 50 Hz. This resolution is enough to estimate fault point with less than 3.2% error. It has been observed that, processing 2 or 3 period of voltage and current signals do not affect the accuracy.

The harmonics in the spectrum of the filtered voltage signal with higher amplitudes are related with the fault location. These harmonics can be extracted from FFT spectrum by using a peak detection technique. As can be seen from Fig. 3 and described previously there are more than one harmonic associated with the fault. All fault related harmonics can be extracted from FFT spectrum as follow: First, all the harmonics which are over average value are detected. Then, they are sorted by their amplitude values. Finally, wanted numbers of harmonics with big value are sorted according to their frequencies and results are stored in an array for processing.

In the voltage signal, which is sampled at one end of power system, source frequency is dominated. This makes it difficult to detect fault related frequencies. For this, prior to FFT, the sampled voltage signal should be high-pass filtered. For filtering 5th order a high-pass-filter with a cut-off frequency of 60Hz is used. After filtering the fundamental frequency, harmonics associated with fault will be easier to detect.

Fig. 2 shows the voltage and current signal when fault occurs at 120 km obtained by state-space method using 200 L-sections. The source inductance is 10 mH. Fig. 3 shows power spectrum density of voltage and current signal for the same fault. As it can be seen from the figure, fault related harmonics are present at both spectrums. Hence, with the help of determined harmonic frequencies and the Eq (16), fault distance can be estimated. The estimated fault distance from measured end by using only first harmonic of current signal and total percentage error are shown in Table 1. The error also covers the error due to lumped parameter approximation of the transmission line and error associated with FFT. Fault detection is also carried out for symmetrical three-phase faults with approximately same accuracy to that achieved in single-phase fault.

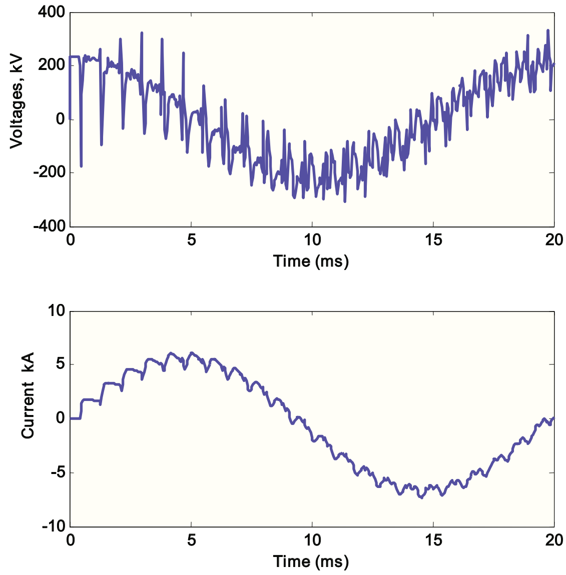
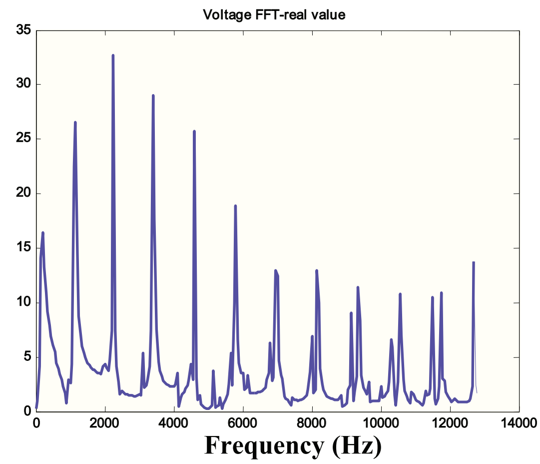
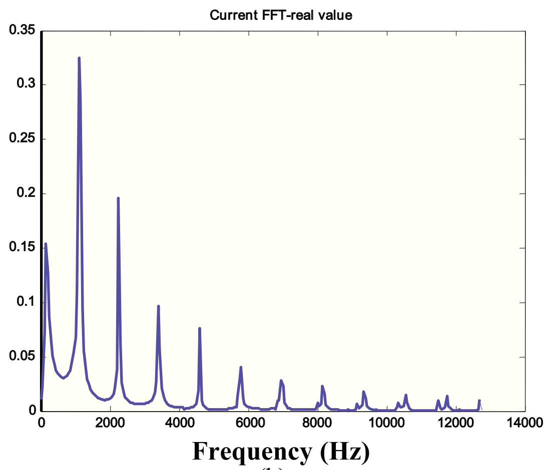


Fig. 2. Transient a) voltage and b) current waveforms for a fault at 120 km from the sending-end.



(a)



(b)

Fig. 3. Transient response in frequency domain; a) voltage, b) current.

Table 1. Measured fault distance and accuracy for several fault locations.

Fault Distance (km)	Measured 1st harmonic frequency (Hz)	Measured fault distance (km)	Percentage Error
40	3550	41.64	0.47
80	1800	82.13	0.61
120	1200	123.19	0.91
160	900	164.25	1.22
200	750	197.10	0.83
240	600	246.38	1.83
280	550	268.78	3.20
320	450	328.51	2.43

Table 2 and 3 show the effect of fault resistance and phase angle on the accuracy of fault distance for a fault at 120 km, respectively. As it can be seen from the tables, the fault resistance and phase angle do not affect the accuracy. However, as the method is based on the travelling wave theory, reactive elements such as source inductance may affect the accuracy, which is investigated by varying the source inductance. The accuracy on the locating fault distance for different values of the source inductance is given in Table 4.

Table 2. Measured fault distance and accuracy for a fault at 120 km for different values of fault resistance.

Fault Resistance (Ω)	Measured Fault Distance (km)	Percentage Error
1	123.19	0.91
5	123.19	0.91
10	123.19	0.91
20	123.19	0.91
50	123.19	0.91

Table 3. Measured fault distance and accuracy for a fault at 120 km for different phase angles.

Phase angle in degree	Measured Fault Distance (km)	Percentage Error
0	123.19	0.91
30	123.19	0.91
60	123.19	0.91
90	118.26	0.50
120	123.19	0.91
150	123.19	0.91

Table 4. Measured fault distance and accuracy for a fault at 120 km for different values of the source inductance.

Source Inductance (mH)	Measured Fault Distance (km)	Percentage Error
0.0	118.26	0.50
1.0	123.19	0.91
10	134.39	4.11

4. Conclusion

A travelling wave based fault detection technique for transmission lines is developed in this paper. Fault distance is detected by processing transient voltage and current waveforms transformed into the frequency domain using Fast Fourier Transform (FFT), considering the frequency of travelling wave with lower frequency. Simulation results show that the accuracy of the method is about %1 and phase angle at fault instant and fault resistance do not affect the accuracy of the method. Currently determination of fault distance of single-phase lines and symmetrical faults at three-phase lines is carried out. The method will be generalized for other types of faults in three-phase lines. Elimination of the effect of reactive elements is under study.

5. References

[1] H. Ha, B. Zhangg, and Z. Lv, "A novel principle of single-ended fault location technique for EHV transmission lines" *IEEE Trans Power Deliver*;18(4):1147–51, 2003

[2] S. Guobin, S. Jiale, and G. Yaozhong, "An accurate fault location algorithm for parallel transmission lines using one-terminal data", *Int. Journal of Electrical Power and Energy Systems*, Volume: 31 Issue: 2-3 Pages: 124-129, FEB-MAR 2009.

[3] J. Sadeh, A. M. Ranjbar, N. Hadjsaid, and R. Feuillet, "Accurate fault location algorithm for power transmission lines" *Europe Trans Electr Power (ETEP,)* 10(5):313–8, 2000.

[4] C. Pereira, and C. Zanetta, "Fault location in transmission lines using one-terminal post-fault voltage data", *IEEE Trans Power Deliver,* 19(2):570–5, 2004.

[5] J. Izykowski, E. Rosolowski, and M. M. Saha, "Locating fault in parallel transmission lines under availability of complete measurements at one end", *IEE Proc Generation Transmission Distribution*, 151(2):268–73, 2004.

[6] Gopalakrishnan, M. Kezunovic, S. M. McKenna, and D. M. Hamai, "Fault Location Using the Distributed Parameter Transmission Line Model", *IEEE Transactions on Power Delivery*, VOL. 15, NO. 4, pp. 1169-1174, OCTOBER 2000.

[7] J. Suonan, S. P. Gao, G. B. Song, et al., "A Novel Fault-Location Method for HVDC Transmission Lines", *IEEE Transactions on Power Delivery*, Volume: 25, Issue: 2, Pages: 1203-1209 , APR 2010.

[8] Z. M. Radojevic, C. H. Kim, M. Popov, G. Preston, and V. Terzija, "New approach for fault location on transmission lines not requiring line parameters," presented at the Int. Power System Transients, Kyoto, Japan, Jun. 2–6, 2009.

[9] Y. Liao and S. Elangovan, "Unsynchronized two-terminal transmission line fault location without using line parameters", *Proc. Inst. Elect. Eng., Gen., Transm. Distrib.*, vol. 153, pp. 639, 2006.

[10] Y. Liao, and N. Kang, "Fault-Location Algorithms Without Utilizing Line Parameters Based on the Distributed Parameter Line Model", *IEEE Transactions on Power Delivery*, Vol. 24, No: 2, pp. 579-584 APR 2009.

[11] C.A. Apostolopoulos, and G.N. Korres, A Novel Algorithm for Locating Faults on Transposed/Untransposed Transmission Lines Without Utilizing Line Parameters IEEE Trans. Power Delivery, vol. 25, pp. 2328 – 2338, no. 4, 2010.

[12] Z. Q. Bo, G. Weller, and M. A. Redfern, "Accurate fault location technique for distribution system using fault generated high-frequency transient voltage signals", *IEE Proceedings-Generation, Transmission and Distribution*, vol. 146, pp. 73-79, 1999.

[13] D.W.P. Thomas, R.J.O. Carvalho, and E.T. Pereira, "Fault location in distribution systems based on traveling waves," *IEEE Power Tech Conference Proceedings*, 2003, Bologna, vol. 2.

[14] F. H. Magnago, and Ali Abur, “Fault Location Using Wavelets”, *IEEE Transactions on Power Delivery*, Volume 13, No.4, 1998.

[15] M. J. Reddy, and D. K. Mohanta, “A wavelet-fuzzy combined approach for classification and location of transmission line faults”, *Electrical Power and Energy Systems*, Volume 29, s.669-678, 2007.

[16] P.S. Bhowmik, P. Purkait, and K. Bhattacharya, “A novel wavelet transform aided neural network based transmission line fault analysis method”, *Electrical Power and Energy Systems*, Volume 31, s.213-219, 2009.

[17] R. Salat, and S. Osowski, “Accurate fault location in the power transmission line using support vector machine approach,” *IEEE Transactions on Power Systems*, Vol. 19, (2) pp. 979-986, 2004.

[18] M. S. Mamis, and M. Koksal “Solution of eigen problems for state-space transient analysis of transmission lines”, *Electric Power Systems Research,* 55 (1): 7-14 JUL 5 2000.

[19] M. S. Mamis, and A. Nacaroglu, “Transient voltage and current distributions on transmission lines”, *IEE Proceedings-Generation Transmission and Distribution,* 149 (6): 705-712 NOV 2002.

[20] Stevenson, Elements of Power System Analysis, Mc Graw Hill, 1989.