International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:13, No:7, 2019

Fault Location Identification in High Voltage Transmission Lines

Khaled M. El Naggar

Abstract—This paper introduces a digital method for fault section identification in transmission lines. The method uses digital set of the measured short circuit current to locate faults in electrical power systems. The digitized current is used to construct a set of overdetermined system of equations. The problem is then constructed and solved using the proposed digital optimization technique to find the fault distance. The proposed optimization methodology is an application of simulated annealing optimization technique. The method is tested using practical case study to evaluate the proposed method. The accurate results obtained show that the algorithm can be used as a powerful tool in the area of power system protection.

Keywords—Optimization, estimation, faults, measurement, high voltage, simulated annealing.

I. Introduction

THE primary task of the protection system in electrical networks, is to detect faults occurring on transmission lines as fast as possible. Another important job is to locate the fault point accurately. Therefore, it is essential to use an accurate detection method that can predict and locate the faulty section at high degree of accuracy in order to reduce the interruption time Different methods have been proposed, some of these methods are based on state estimation techniques while others are based on heuristic search techniques. Both static and dynamic techniques were presented within the state estimation scope. The least error squares and least absolute value were widely proposed. These methods represent the static family. In [1], authors presented a method relies on the well-known least error square (LES) estimator. The technique uses digital samples for the captured waveforms of both voltage and current at the sending end to find the impedance up to the fault point. The fault distance is consequently calculated by assuming that the line reactance is proportional to the line length up to the fault point. Kalman Filtering (KF) and weighted least absolute value dynamic filters are also widely presented as dynamic state estimation techniques. In [2], the use of dynamic filter to estimate the fault location on-line is presented. In this paper the impedance up to the fault point is calculated using the collected voltage and current samples at the sending end terminals [3]. The widely used discrete fast Fourier transform (FFT) was implemented by Sheng in [4]-[6]. In these works, methods based on discrete Fourier transform that uses voltage and currents samples at both ends of the transmission line was used. In application of the FFT, there are some assumptions imbedded. These assumptions based on the fact that the signal is stationary; and the sampling theorem is satisfied. Application of the FFT transforms algorithm without pay attention to these basic assumptions would lead to inaccurate results.

Artificial neural networks (ANN) and Expert systems (ES) techniques have been suggested and used in this field also [3]. Fukui [7] used a method based on expert systems. He claimed that the method can estimate the fault section using the information available at protective relay. Reference [8] gives a review for ANN based techniques used in this area and discusses both advantages and disadvantages. Heuristic search techniques such as particle swarm optimization (PSO) and genetic algorithm (GA) methods have been also widely presented. The use of genetic algorithms for fault section estimation in sub-transmission networks is presented in [9], [10].

A comprehensive review on the methods used for fault detection, classification and location in transmission lines and distribution systems, is well presented and evaluated in [11].

This paper presents an efficient method based on simulated annealing optimization technique (SA) for locating fault point on transmission lines. In this work the only the sending end short circuit current are used to formulate an overdetermined system of equations. All variables are expressed as a function of the distance up to the fault point. The problem is presented as a mixed estimation and optimization one. The objective is to minimize the absolute error in estimated state parameter. Results obtained are discussed. It is shown that the proposed technique efficiently estimates the fault location during three phase short circuit events. It is evident that the technique can be extended to cover all types of faults including unsymmetrical [3].

II. Mathematical Modeling

The power system shown in Fig. 1 is used to perform the study. It is assumed that the fault happens at different locations from the sending end terminals. For simplicity and without losing the generality, the three-phase symmetrical short circuit current is expressed as [3]:

$$i(t) = E\sin(\omega t+\theta)\left[\frac{1}{x_{deq}} + e^{-t/\tau'_d}\left(\frac{1}{x'_{deq}} - \frac{1}{x_{deq}}\right) + e^{-t/\tau''_d}\left(\frac{1}{x''_{deq}} - \frac{1}{x'_{deq}}\right)\right] \quad (1)$$

Khaled M. EL-Naggar is with the Department of Electrical Engineering, Collage of Technological Studies, the Public Authority for Education & Training, Kuwait (e-mail: Knagggar@ieee.org).

where i(t) the symmetrical short circuit current, E represent the machine induced emf and θ represents the phase angle of the voltage, also the transient and subtranisent reactance's are presented as a function of the line length to the fault point as:

$$\begin{aligned} x_{deq} &= x_d + x_T + x_{TL} * L \\ x'_{deq} &= x'_d + x_T + x_{TL} * L \\ x''_{deq} &= x''_d + x_T + x_{TL} * L \end{aligned} \quad (2)$$

where τ'_d is the transient short circuit time constant, τ''_d is the sub-transient short circuit time constant, x_T is the transformer per unit reactance, x_{TL} is the transmission line reactance per mile, L is the length of line up to the fault point:

Fig. 1 System under consideration

For simplicity we can neglect the subtransient part. Indeed this will not affect the accuracy providing that data considered after the subtransient period. Now, (1) can be rewritten after using the first three terms of Taylor expansion as:

$$i(t) = E\{sin\omega t cos\Theta + cos\omega t sin\Theta\}\{A + B(1 - tc + \frac{c^2t^2}{2} - \frac{c^3t^3}{6})\} \quad (3)$$

where: $A=(1/x_d)$, $B=(1/x_d' - 1/x_d)$ and $C=(1/\tau_d')$.

$$\begin{aligned} i(t) = {} & Esin\omega tcos\Theta\}\{A + B\} + E\, cos\omega t sin\Theta\{A + B\} - BCE\, t\{\, sin\omega t cos\Theta\} \\ & - BCEt\{cos\omega t sin\Theta\} + \frac{c^2t^2BE}{2}\{sin\omega t cos\Theta\} \\ & + \frac{c^2t^2BE}{2}\{cos\omega t sin\Theta\} - \frac{c^3t^3BE}{6}\{sin\omega t cos\Theta\} \\ & + \frac{c^3t^3BE}{6}\{cos\omega t sin\Theta\} \end{aligned} \quad (4)$$

The symmetrical short circuit current flowing at the machine terminal is sampled at a pre-selected rate at equal time intervals, Δt , there will be m equations one for the current at each time sample i(t), starting from t_1 and ending at t_m . Knowing that the samples Z_1 to Z_m are available, and the fundamental frequency is known, [3]

The following discrete system of equations can be written:

$$\begin{bmatrix} Z(1) \\ Z(2) \\ Z(3) \\ Z(4) \\ Z(5) \\ Z(6) \\ \dots\dots \\ Z(m) \end{bmatrix} = \begin{bmatrix} Esin\,\omega\, t_1 & \cdots & -(1/6)\, t^3\, E\, cos\,\omega\, t_1 \\ \vdots & \ddots & \vdots \\ Esin\,\omega\, t_m & \cdots & -(1/6)\, t^3\, E\, cos\,\omega\, t_m \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ \dots \\ e_m \end{bmatrix} \quad (5)$$

In a compact form we can write:

$$[\, Z(t)\,] = [H(t)\,][\, X\, (t\,)\,] + [\, e(t)\,] \quad (6)$$

where [Z(t)] is the m x 1 current samples vector; 0[H(t)] is the m x 8 information vector which can be calculated off- line; [X(t)] are the 8 x 1 state vector to be estimated, from which x_d , x_d', T_d' can be obtained; [e(t)] is the m x 1 unknown measurements error vector assumed to be a white (uncorrelated) sequence with the following statistics; E{e(k)}=0, E{e(k)e(j)^T }= R(k) only if k=j, otherwise it equals 0.

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix} = \begin{bmatrix} cos\Theta\{A + B\} \\ sin\Theta\{A + B\} \\ BCcos\Theta \\ BCsin\Theta \\ BC^2cos\Theta \\ BC^2sin\Theta \\ BC^3cos\Theta \\ BC^3sin\Theta \end{bmatrix} \quad (7)$$

and the information matrix elements as:

$$\begin{bmatrix} H(I,1) \\ H(I,2) \\ H(I,3) \\ H(I,4) \\ H(I,5) \\ H(I,6) \\ H(I,7) \\ H(I,8) \end{bmatrix}^T = \begin{bmatrix} Esin\,\omega\, t \\ Ecos\,\omega\, t \\ -tEsin\,\omega\, t \\ -tEcos\,\omega\, t \\ -0.5t^2Esin\,\omega\, t \\ -0.5t^2Ecos\,\omega\, t \\ -(1/6)\, t^3\, E\, sin\,\omega\, t \\ -(1/6)\, t^3\, E\, cos\,\omega\, t \end{bmatrix}^T \quad (8)$$

where I = 1,2,…..m. (5) and (8) represent the problem in state space form. In order to find the fault distance (L), it is required to find the state vector [X]. With state vector and applying (2), (9), and (10), the fault point can be located using the following simple equations:

$$\begin{aligned} x_{deq} &= -(F^2/G - M) \\ x'_{deq} &= 1/M \\ \tau'_d &= F/G \end{aligned} \quad (9)$$

$$\begin{aligned} M &= \sqrt{x_1^2 + x_2^2} \\ F &= \sqrt{x_3^2 + x_4^2} \\ G &= \sqrt{x_5^2 + x_6^2} \end{aligned} \quad (10)$$

Using (2), the length L can be found from any of the three. It worthwhile to notice that results from the three equations can be slightly different. The values presented in Tables I and II are the average.

III. Parameter Estimation by Simulated Annealing

SA emulates the physical gradual cooling process (called annealing) that produces high quality crystals, i.e. better strength properties, in metals. The two major steps in SA are the transition mechanism between states and the cooling schedule with the objective being finding the state with minimum energy. Forming a perfect crystal is simply done by properly controlling temperature in the annealing process. In

SA, a new solution candidate is randomly generated at each iteration. A probability distribution with a scale proportional to the control parameter, i.e. temperature, governs the distance of the new solution candidate from the existing solution. Measure of solutions' goodness is made by computing and comparing the objective function values. The temperature parameter decreases based on a cooling schedule as the algorithm converges to the optimal solution.

This optimization technique was proposed independently by Kirkpatrick et al. in 1983 [15] and by Cerny in 1985 [16]. They have noted that alternative physical states of the matter resemble the solution space of an optimization problem and the objective function of an optimization problem corresponds to the free energy of the material. Forming a perfect crystal corresponds to finding the optimal solution whereas a crystal with defects corresponds to finding a local solution. In both papers, SA was introduced to solve combinatorial problems by adapting the crystallization process model developed by Metropolis et al. [17]. This model generates a sequence of states of a solid and assumes that the probability for a physical system to have a certain energy level E is proportional to Boltzmann factor $e^{\frac{-E}{k_B * T}}$, where K_B denotes the Boltzmann constant, when the thermodynamic equilibrium is reached at a given temperature T. Assuming a solid in initial state xi with energy level E_i and the next state x_j with energy E_j, if the difference between the two energy levels is less than or equal to zero, the new state x_j is accepted. Otherwise, if the difference is greater than zero, the new state is accepted with probability

$$P(E,T) = e^{\left(\frac{E_i - E_j}{k_B * T}\right)} \quad (11)$$

The general proposed SA algorithm presented here is basically an optimization technique. To use the algorithm as an estimator, it is necessary to formulate the objective function in such away that minimizes the absolute estimation error. The algorithm used in this work can be summarized as follows:

Step 0: Initialize the temperature, $T_{initial}$.
Step 1: Generate some initial random solution, x_i(at step i).
Step 2: Evaluate the objective function,
Fi (in our case Fi = Ei).
Step 3: After certain amount of iterations, the temperature is reduced. If the temperature criterion is satisfied go to step 10.
Step 4: If the iteration is satisfied go to step 9.
Step 5: Generate a new solution, x_j.
Step 6: Evaluate the objective function *Ei*.
Step 7: Acceptance test: if *Ej-Ei < 0,* then store the new solution. Otherwise, accept the new solution with a probability, *P(E,T).*
Step 8: If the objective function remains the same consecutive times, go to step 9 else go to step 4.
Step 9: Reduce the temperature and go to step 3.
Step 10: Stop if termination criterion is met.

IV. Results

The high voltage system described earlier in Fig. 1, is used to perform the study. The system consists of an equivalent generator 25 MVA, 13.8 KV feeding a load through 30 MVA, 13.8/69 KV transformers with 0.1 pu reactance and a short transmission line. The Transmission Line is 50 miles long; the line has impedance of 0.2+j0.8 ohms per mile with neglected capacitance [3].

$$x_d = 1.7 \text{ p.u.}$$

$$x_d' = 0.256 \text{ p.u.}$$

$$\tau_d' = 0.26 \text{sec.}$$

$$x_d'' = 0.185 \text{ p.u.}$$

$$\tau_d'' = 0.0276 \text{ sec.}$$

Different study cases are performed including different dat window size, different fault location and different sampling rate. Samples of the resulted are presented and discussed in next sections.

A. Effect of Data Window Size

The effect of the data window size is examined in this section. A three phase short circuit is assumed to happen at distance of 20 mile from the sending end point. Figs. 2 and 3 show the simulated phase current following In Fig. 2 the phase angle was zero while in figure three the angle was 0.1 radians. Extensive runs were performed, sample of the results are presented here. Table I summarizes the results of the first case (phase angle=0). In this table, we used data window size from 1 to 8. The sampling rate is 1 kHz while the window covers from one complete cycle to eight complete cycles. It is assumed that the fault exact location is 20 miles. The steady state voltage is 1 pu while the phase angle is zero. Examining the table, it is clear that the all window sizes give accurate results. Considering the calculation time, and knowing that the process is an on-line process where the detection time is an important factor, the window size 1 can be recommended and chosen for further studies as it gives very small error. One cycle support the fast decision. With less number of samples the algorithm can detect the fault accurately and very fast.

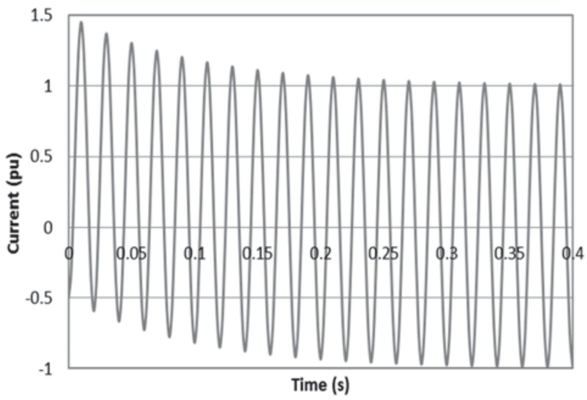

Fig. 2 Symmetrical short circuit current (phase angle=0)

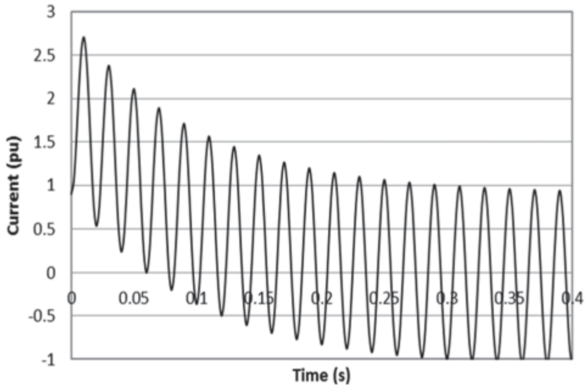

Fig. 3 Symmetrical short circuit current (phase angle=0.1 rad)

TABLE I
ESTIMATED FAULT LOCATION (L) IN MILES: EXACT FAULT LOCATION = 20 MILES, VARIABLE WINDOW SIZE

Number of samples	Window size	Estimated fault location (miles)
10	1	20.11
20	2	20.11
30	3	20.14
40	4	20.13
50	5	20.13
60	6	20.23
70	7	20.20
80	8	20.20

B. Effect of Sampling Rate

As concluded in the previous section, a data window size of 1 cycle gives accurate results. Therefore, this window will be used in the following study case. In this case, a one cycle is used with different sampling rates to evaluate the behavior of the algorithm. Sampling rates used started from 1000 Hz up to 4000 Hz in step of 500 Hz. Results are displayed in Table II. The window size is fixed in this table at one. The exact fault is still at 20 miles. The table confirms the accuracy of the technique. The accuracy is almost the same for number of samples up to 40, after this, results starts to be inaccurate. The higher sampling rate could cause redundancy in the measurement set. The algorithm starts to give inaccurate results. As long as the sampling theorem is satisfied, the higher sampling rate is not recommended. In our study and based the sampling theorem it is recommended to have sampling frequency higher than 100 Hz. It is clear that 1000Hz. will be more than enough.

TABLE II
ESTIMATED FAULT LOCATION (L) IN MILES
EXACT FAULT LOCATION = 20 MILES, VARIABLE SAMPLING RATE

Number of samples	Sapling rate	Estimated fault location (miles)
20	1000	20.11
30	1500	20.19
40	2000	20.16
50	2500	20.46
60	3000	20.46
70	3500	22.71
80	4000	23.15

V. CONCLUSION

A digital heuristic-based method for on-line fault location in transmission lines is presented in this paper as a powerful tool in the area of power system protection. The technique is a dynamic algorithm and successfully applied to the problem of allocating fault point in overhead transmission lines. The proposed method uses only a set of digital measurements of short circuit current waveform at the sending end terminal only. The formulation is presented in state space form for solving estimation problem. Short circuit current at the sending end of the transmission line at different window sizes and different sampling rates are generated and sampled to test the proposed algorithm. The proposed algorithm is then used to find the exact fault distance. Results obtained show that the technique can be used as on-line method for determination of fault location in only one cycle with a very high degree of accuracy. Data collected only at the sending end terminals, no need for synchronization between data collected at both transmission line ends.

REFERENCES

[1] M.S. Sachdaev and M.A. Baribeu, “A New Algorithm for Digital Impedance Relay.”, IEEE Tran. on Power Apparatus & Systems, Vol. PAS-98, No.6, pp.2232-2238, Nov-Dec.1979.
[2] Hanafy M. Ismail and Khaled M. EL-Naggar , “ A Dynamic On-Line Fault Location Algorithm Based on A Discrete Filter for HV Transmission Lines”, Third Regional Conference of CIGRE Committees in Arab Countries, Doha, Qatar, Vol. 2, pp. 75-80, May 1999.
[3] K.M.E-Naggar, “A Genetic Based Fault Location Algorithm For Transmission Lines”,16th International Conference on Electricity Distribution (CIRED 2001/IEE), Amsterdam, Netherlands,Vol.3, June 2001.
[4] Lino Bo Sheng and S. ELangovan, “A Fault Location Algorithm for Transmission Lines”, Electric Machines & Power Systems Journal, Vol. 26, pp.991-1005.
[5] C. S. Chen , C. W. Liu and J. A. Jiang "Application of combined adaptive Fourier filtering technique and fault detector to fast distance protection", IEEE Trans. Power Del., vol. 21, no. 2, pp.619 -626, 2006.
[6] Abdollahi, A., Peng Zhang, "Precise removal of decaying dc in DFT algorithm for power system measurement," Power and Energy Society General Meeting, 2012 IEEE , vol., no., pp.1,7, 22-26 July 2012.
[7] C.Fukui and J. Kawakami, “An Expert System for Fault section estimation Using Information from Protective Relays and Circuit Breakers”, IEEE. Trans. Power Delivery, PWRD-1 (4), pp.83-90, 1988.
[8] M. EL-Sharkawy and D. Niebur, 1996, “Artificial Neural Networks with Applications to Power Systems”, IEEE Power Engineering Socity, A Tutorial Course.
[9] Fushuuan Wen, Zhenxiang Han, “Fault Section Estimation in Power Systems Using Genetic Algorithm”, Electric Power System Research Journal, Vol.34, pp.165-172, 1995.
[10] Fu Xiang and Zheng Zheng-Jian, "Research on complex electronic equipment fault location based on improved Genetic Algorithm," 2010 2nd International Conference on Computer Engineering and Technology, Chengdu, 2010, pp. V1-454-V1-457.
[11] K. Chen, C. Huang and J. He, "Fault detection, classification and location for transmission lines and distribution systems: a review on the methods," in *High Voltage*, vol. 1, no. 1, pp. 25-33, 4 2016.
[12] M. Singh, B. K. Panigrahi and R. P. Maheshwari, "Transmission line fault detection and classification," 2011 International Conference on Emerging Trends in Electrical and Computer Technology, Tamil Nadu, 2011, pp. 15-22.
[13] M. Davoudi, J. Sadeh and E. Kamyab, "Parameter-free fault location for transmission lines based on optimisation," in *IET Generation, Transmission & Distribution*, vol. 9, no. 11, pp. 1061-1068, 8 6 2015.
[14] D. Ritzmann, P. S. Wright, W. Holderbaum and B. Potter, "A Method for Accurate Transmission Line Impedance Parameter Estimation," in *IEEE*

Transactions on Instrumentation and Measurement, vol. 65, no. 10, pp. 2204-2213, Oct. 2016.

[15] Hosam K. Youssef, Khaled M. EL-Naggar, “Genetic- Based Algorithm for Identification of Synchronous Machine Parameters Using Short Circuit Tests”, International Journal of Energy Research, Vol.24, 2000, pp.877-885.

[16] S. Kirkpatrick, C. D. Gelatt Jr, and M. P. Vecchi, "Optimization by simulated annealing," Science, vol. 220(4598), pp. 671-680, 1983.

[17] V. Cerny, "Thermodynamical approach to the traveling salesman problem: an efficient simulation algorithm," Journal of Optimization Theory and Application, vol. 45(1), pp. 41-51, 1985.

[18] N. Metropolis, A. W. Rosenbluth, M. N. Rosenbluth, and A. H. Teller, "Equation of state calculation by fast computing machines," Journal of Chemical Physics, vol. 21, pp. 1087-1092, 1953.