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Genetic Algorithm Based Fault Locator for Transmission Lines

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Abstract

This paper presents a novel application of Genetic Algorithm (GA) in implementation of the Differential Equation Algorithm (DEA) for fault location on transmission lines. The approach consists in first formulating the problem as that of minimization of the error between measured and estimated instantaneous voltage at the relay location. GA is then used as a tool, for finding out the optimum solution. Inherent advantages of GA like good ability to reach global optimum, robustness etc. are thus exploited. Comparison with results obtained using other conventional methods like Simultaneous Differential Equation (SDE), Non-Linear Programming (NLP) and Multivariable Series Least Squares (MVS-LSQ) techniques reveals that the proposed approach using GA has a superior performance. Thus GA should find a place in the tool-bag of protection engineers.

Keywords: Differential Equation Based Algorithm, Fault Location, Genetic Algorithm, Lumped Series Model, Pi Section Model, Simultaneous Differential Equation Technique

1. Introduction

Relays are used to sense the fault and issue trip signal to appropriate circuit breaker(s) so as to disconnect the faulty part from the system to minimize the foot-print of faults. Ideally a relay should, not only detect the correct zone in which fault lies but also zero-in on the exact fault location. Detection of correct zone is required for selectively isolating the faulty element from rest of the system using circuit breakers, while accurate fault location is needed so that maintenance crew can visit the spot and carryout repairs. Thus accurate fault location helps in speeding up the job of restoring the faulty line to its healthy state. Historically relays based on electro-mechanical technology were good at inferring correct zone but left much to be desired as far as accurate fault location was concerned. However with the advent of numerical relays the relays themselves can be endowed with fault location abilities by adding appropriate software routines.

Digital relaying was first contemplated during the late 1960s[1,2]. In one of the earliest papers on the subject, Rockefeller suggested that all the power system components could be protected using digital computers[3]. In 1970, McInnes and Morrison proposed that transmission line be modeled as a series R-L circuit, which resulted in a first order differential Equation[4]. This can be used to find the resistance and inductance of line using only three samples. In 1977, Phadke, Ibrahim, and Hlibka presented a method to determine the distance to the fault point from transmission line terminal using symmetrical components of voltage and currents rather than using phase voltages and currents[5]. They considered the use of digital filters, to remove the transient components, contained in the voltage and current waveform during fault, and

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to produce the symmetrical components of the filtered quantities. Smolinski, in 1979, proposed an algorithm which included a shunt capacitive element along with the series R-L model, giving a single PI section representation of transmission line[6]. This resulted in a second-order differential Equation.

This can be used to determine the faulted line's resistance and reactance using only four samples of post fault current and voltage.

A method based on reactive power using current and voltage phasors from one terminal was proposed by Takagi *et al*[7]. Jeyasurya, and Smolinski described a method for seeking out the best or optimal combination of digital distance relay and digital filter algorithm for transmission line protection[8]. Girgis *et al* and Gopalkrishnan *et al* have used voltage and current phasors from both the ends for location of fault[9,10]. A fault-location method for transmission lines using only voltage measurements at both ends of the line, eliminating the inherent error due to CT has been presented by Bramha, and Girgis[11]. A neural network approach for fault location in single-and-double circuit transmission lines has been presented in[12–14]. Liao presented, a transmission line fault location algorithm based on distributed parameter line model by utilizing unsynchronized voltage and current measurements from two terminals of the line[15], and transmission line fault location algorithms without requiring line parameters[16]. Lin, Weng, and Wang have presented a generalized method to improve the location accuracy of single-ended sampled data and lumped parameter model based fault locator[17]. A differential equation-based fault locator for unified power flow controller-based transmission line using synchronized phasor measurements has been presented by Samantaray, Tripathy, and Dash[18]. Kang *et al* have proposed a fault-location algorithm for ultra-high-voltage un-transposed parallel transmission lines that only uses the voltages and currents at the local end[19]. Silve *et al* have presented, a methodology based on the low- and high-frequency components of the transient signals originated from fault situations registered in the terminals of a system, for fault location in three terminal lines[20].

Fault-location methods can be divided into three categories: 1) methods that are based on fault created traveling waves; 2) methods that use non fundamental higher frequency components of currents and voltages; and 3) methods that use the fundamental frequency voltages and currents measured at the terminals of a line[21]. In the last method, the line impedances as seen from the relay locations are calculated and using this, the distance to the faults is estimated. The lumped series parameter model and the pi-section model can be used to find the value of impedance between relay location and fault point, by applying SDE technique, which in turn gives the distance (location) of the fault[22]. These estimates are approximate but of sufficient accuracy to determine the zone of protection. However, much more accurate estimates of the fault location are desirable for inspection, maintenance, and repair of the actual fault[2].

In an attempt to improve the accuracy, in this paper, fault location has been formulated as a nonlinear optimization problem which is then solved using GA. It is well known that the conventional nonlinear optimization techniques, like steepest-descent, conjugate gradient, Newton's method etc., and have a tendency of getting trapped in local optimum point. However, GA offers a more robust method to find the optimum, thus paving the way to a more accurate estimate of *R* and *L* parameters of the faulted line. Due to the fact that GA is a multipoint search rather than a single point search, GA samples a much larger solution space and thus heightens the possibility of hitting upon the global optimum. Sometimes a random initial population (in GA) results in over sampling of some regions and sparse sampling in others. This may cause the GA to converge to a value which is near a local optimum. To avoid this pitfall a uniform random number generator, which produces uniform random samples, has been used in this paper. It is thus shown that the fault location can be treated as an optimization problem and can be efficiently solved using GA technique.

Thus the main contributions of this paper are (i) formulation of the problem of fault location using DEA as a problem in nonlinear optimization, and (ii) application of GA to arrive at the optimum solution of the fault location problem.

2. Differential Equation based Algorithm

In this approach the transmission line is modeled by either lumped series impedance or a single PI section, which involves line parameters up to the fault. The instantaneous values of current and voltage at the relay location are related through a differential equation.

2.1 Lumped Series Impedance based Algorithm

The lumped series impedance based algorithm assumes that the current and voltage waveforms contain a DC component but are otherwise free from high frequency components. In other words, it is assumed that high frequency waveforms are filtered-out from the original faulted waveforms using low pass filtering[1]. This is equivalent to assuming that the filtered voltages and currents are produced by a lumped-series transmission-line model, as shown in Figure 1, where *R* and *L* are the total resistance and inductance of the line from relay location to the fault point.

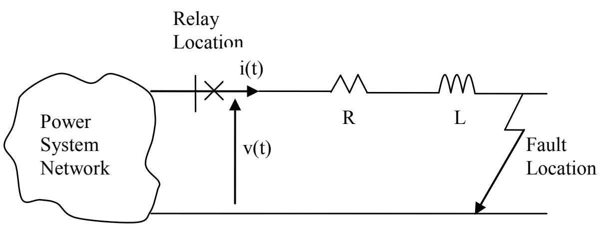

Figure 1. Representation of Transmission Line Using Lumped-Series Circuit Parameters

Therefore from the basic principle of circuit theory, $v(t)$ and $i(t)$ are related by

$$v_k = Ri_k + L\frac{di_k}{dt} \tag{1}$$

Let v_k and i_k be the voltage and current samples at time ikand let Δt be the sampling time interval. The derivative of the current at the k^{th} time interval with respect to time (di_k/dt) can be approximately determined using Equation (2)

$$\frac{di_k}{dt} = \frac{i_{k+1} - i_{k-1}}{2(\Delta t)} \tag{2}$$

Once the numerical values of *v*, *i* and di/dt are plugged into Equation (1) it becomes a simple algebraic equation in two unknowns; hence one more equation is needed to find the values of unknowns. This is obtained using additional samples of voltage and current at subsequent intervals of time.

2.2 Single PI Section Model Based Algorithm

This algorithm attempts to accommodate the high frequency oscillations, which can occur during faults. This is done by including the capacitance of transmission line using a single PI section representation as shown in Figure 2.

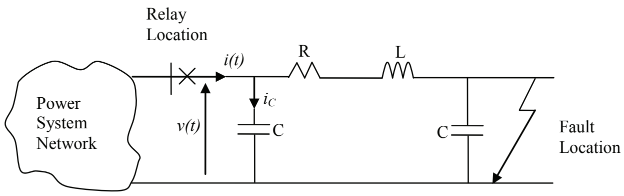

Figure 2. Representation of Transmission Line Using Single Pi-Section Model.

The fault resistance is assumed to be sufficiently small so that the far end line capacitance as well as in-feed from remote end may be neglected[1,6]. The circuit operation can be described by following equation

$$v = R(i - i_c) + L\frac{d(i - i_c)}{dt} \tag{3}$$

where i_c (the current through the capacitor) is given by $C\frac{dv}{dt}$. Hence Equation (3) can be written as

$$v = Ri + L\frac{di}{dt} - RC\frac{dv}{dt} - LC\frac{d^2v}{dt^2} \tag{4}$$

The derivative of current with respect to time is obtained using Equation (2). The first and second derivatives of voltage are obtained using Equations (5) and (6) respectively.

$$\frac{dv_k}{dt} = \frac{v_{k+1} - v_{k-1}}{2(\Delta t)} \tag{5}$$

$$\frac{d^2v_k}{dt^2} = \frac{v_{k+1} - 2v_k + v_{k-1}}{(\Delta t)^2} \tag{6}$$

After plugging in the values of *v*, *i*, di/dt, dv/dt and dv^2/dt^2 in to Equation (4) it becomes an algebraic equation in four unknowns, hence a total of four equations need to be written using the voltage and current samples at four different time instants to get the values of the unknowns.

The SDE technique can be used to determine the values of *R* and *L* with lumped series model as well as pi section model of transmission line[1,8]. The detailed procedure of the same has been presented in[22]. The values obtained using SDE technique are approximate and can be used to determine whether the fault is in the appropriate zone of protection.

3. Determination of R and L using GA

GA is an optimization technique inspired by the principles of natural evolution and natural selection. GA allows a population composed of many solutions to evolve under specified selection rules to a state that maximizes the "fitness"[23-25]. GA are explained in[23-26].

For correct location of fault the values of R and L are to be found accurately. This can be achieved with GA approach, by converting the problem of determining R and L into a nonlinear optimization problem, based on a suitable fitness (objective) function

3.1 Defining the Fitness Function

The fitness function can be obtained with the help of sum of square of errors. If the error, which is the difference between measured voltage and calculated voltage, is represented by *er*, then the error at i^{th} time instant can be written as

$$er_i = v_i - v_{i,\,calulated} \tag{7}$$

where v_i is the value of voltage sample at i^{th} time instant, and $v_{i,\,calulated}$ is the value of calculated voltage at i^{th} time instant

The value $v_{i,\,calulated}$ is obtained using Equation (1), in case of lumped series representation, and using Equation (4), in case of single pi section representation of line. The sum of square of errors can be written as

$$\Sigma(error)^2 = (er_2)^2 + (er_3)^2 + ... + (er_{n-1})^2 \tag{8}$$

It should be noted that the errors at t_1 and t_n can not be calculated, since derivative of current and voltage can not be computed at the very first and the very last (n^{th}) sampling instant. The objective is to minimize the sum of squares of errors. Since as per convention, the fitness function should have higher value for better solution, the fitness function can be coded as negative of $\Sigma(error)^2$, or can be coded as sum of squares of errors subtracted from a large positive number (N) as shown in (15). The fitness function considered here is

$$F(x) = N - \Sigma(error)^2 \tag{9}$$

This fitness function is to be maximized. Thus, it is an unconstrained optimization problem and can be solved using GA to obtain the global optimum

3.2 Calculation of Current and Voltage Derivatives

For finding the value of $v_{i,\,calulated}$ at any time instant, the derivatives of current and voltage need to be calculated. The samples of voltage and current at the relay location are available. If 'n' samples of voltage and current (from the VT and CT at the relay location) are available, then the derivatives of current and voltage, at 'n' different time instants, can be calculated using Equations (2), (5), and (6).

3.3 Application of GA

As the values of R and L are to be found out, R and L are treated as variables (parameters). In case of pi section representation of line, there will be an additional variable (C). If n bits are used to represent each parameter, the size of chromosome in case of lumped series representation and pi section representation will be $2n$ bits and $3n$ bits respectively. An initial population of p chromosomes is generated randomly. The population is passed through the fitness function (objective function).

As the objective is to maximize the function, the chromosome giving maximum fitness value is the most fit chromosome. The population is sorted according to decreasing value of fitness. The chromosomes with higher fitness value (upper 50 % of population) survive and are reproduced in the next generation. These are called parent chromosomes and are used for crossover.

Pairs of parent chromosome are selected for mating using some strategy. In this work, pairing from top to bottom was used. Single point crossover is performed between the chromosomes so selected, in which the crossover site is selected randomly and swapping of bits, among the parent chromosome, is done. Crossover generates offsprings. The crossover rate is kept at 50 %. The parent chromosomes along with offsprings are placed together to form the population for the next generation. The population size of p is maintained in all generations.

The 'mutation' is applied after crossover. For mutation the bit position is selected randomly from the chromosome (the chromosomes are also selected randomly) and is replaced by its complement. At this point, one iteration of GA is complete.

The process can be stopped when the most fit chromosome gives the fitness function value greater than a predefined threshold. The final values of R and L are decoded from that chromosome which gives maximum fitness, after terminating the GA

4. Results and Discussions

To test the proposed algorithm, samples of voltage and current were obtained using simulations in, Power Systems Computer Aided Design (PSCAD). A program was developed in MATLAB, for obtaining the value of *R* and *L* using GA. The program was found to give satisfactory results. Two cases (one for lumped series representation and one for single pi section representation) are presented here for demonstration. Number of iterations was considered as the stopping criteria for GA, in the program. The program was tested with different number of iterations (generations in GA). It was found that 40 iterations are sufficient to locate the fault with high accuracy. Performing much less number of iterations cause loss of accuracy, and choosing large number of iterations increases the time required without proportionate gain in accuracy. Hence in the cases presented in sections 4.1 and 4.2, the process was stopped after performing 40 iterations. For the purpose of comparing the results obtained using GA, programs in MATLAB were also developed, for obtaining the value of *R* and *L* using SDE based algorithm, NLP method, and MVS-LSQ method.

It may be noted that in case of fault location problem, the objective function, described by equation (9), is nonlinear in nature. Hence it is an NLP problem. Various methods are available to solve the NLP problem. In this paper, the function available in MATLAB optimization toolbox (fminunc) has been used to find the optimum solution of the fault location problem.

MVS-LSQ method is a technique used to fit faulted current and voltage waveforms, each to a sinusoidal waveform containing a fundamental component, a decaying DC component and harmonics. It uses the least squares method to minimize the fitting error and has the goal of extracting the fundamental components of voltage and current waveforms, in order to calculate the impedance to the fault[1].

4.1 Illustration I

To validate the algorithm, the samples are generated from a single phase equivalent lumped series representation of a 132 kV, 80 km long transmission line as shown in Figure 3. The line has series resistance of 6.4 Ω and series inductance of 0.1056 H, between the relay at one end and a fault on the other end. Samples of voltage and current were generated by simulating this line model in PSCAD and applying a fault at time t = 1.0 s. The voltage and current waveforms are shown in Figure 4. Twenty samples were taken during the fault, with a sampling time interval of 0.001 s, i.e., with a sampling frequency of 1 kHz. These samples were used to find the value of *R* and *L*.

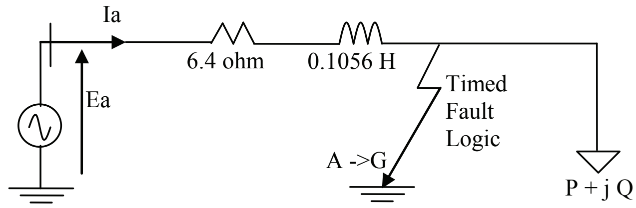

Figure 3. Lumped series model of a faulted transmission line.

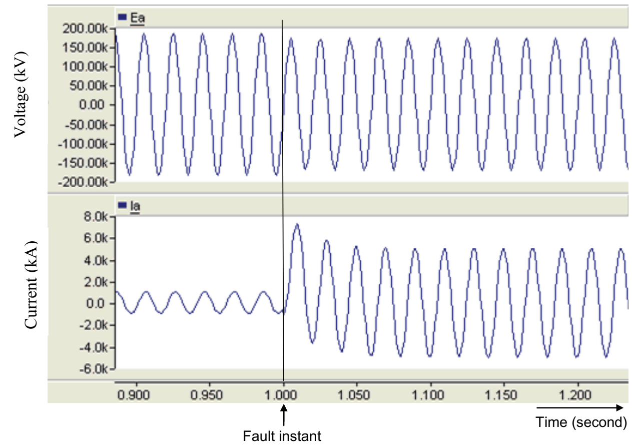

Figure 4. Pre and post fault voltage and current waveforms for lumped series represented transmission line.

The algorithm was tested with different GA parameters. The best values of resistance and inductance are obtained by performing 40 iterations of GA, with following GA parameters,

Population size	= 128
Number of bits per parameter	= 12
Crossover rate	= 0.5 (50%)
Mutation rate	= 0.05 (5%)

The results obtained using GA, SDE, NLP, and MVS-LSQ techniques are shown in Table 1. The percentage error in the estimated values of R and L, using different methods has been presented in Figure 5.

It can be seen that the result obtained using GA are more accurate as compared to those obtained using SDE, NLP, and MVS-LSQ techniques. Further, in case of SDE technique, the values calculated are different at different time instants. The results presented in Table 1 (using SDE technique) are the average values. At many time instants the values have more error than shown in the table. NLP methods, being single point search methods, have a drawback of getting trapped in local optimum point,

Table 1. Results obtained using different methods (Illustration I)

METHOD	ACTUAL VALUES: R = 9.6 Ω, L = 0.1584 H			
	CALCULATED VALUES OF			
	Resistance (R)		Inductance (L)	
	Value (Ω)	% error	Value (H)	% error
SDE	9.0511	5.7177	0.1642	3.6616
NLP	9.9101	3.2302	0.1645	2.4621
MVS-LSQ	9.8422	2.5229	0.1614	1.8939
GA	9.4637	1.4198	0.1611	1.7045

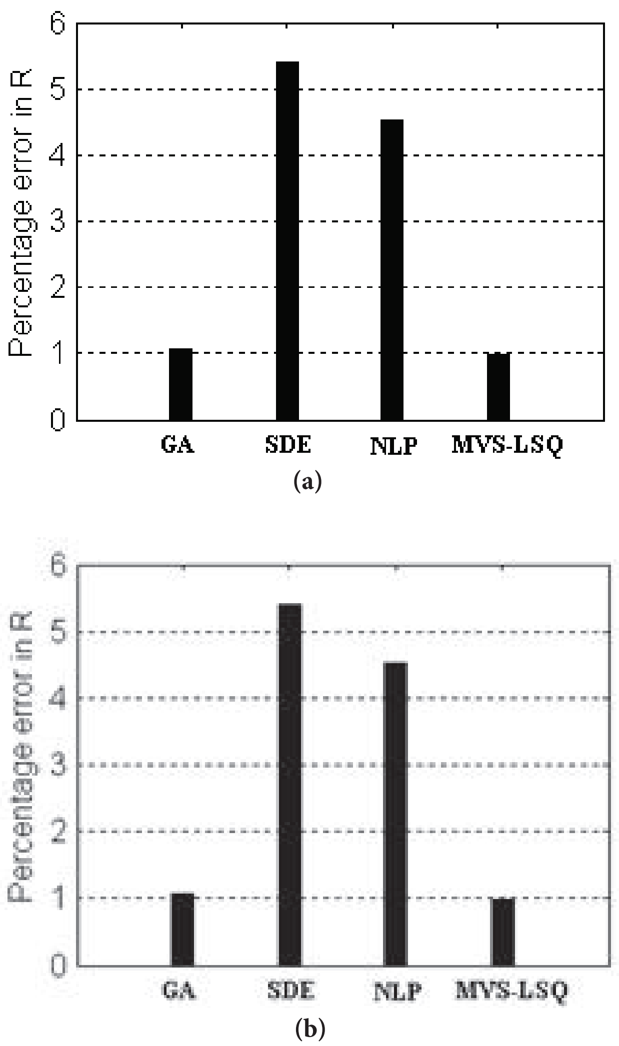

Figure 5. Percentage Error in Estimated Values of. (a) Resistance; (b) Inductance Using Different Methods.

if the initial choice is nearer to the local optimum. Thus the results obtained using NLP technique is dependent on the initial choice. In case of the MVS-LSQ technique the value of R is more accurate, but the value of L suffers from increased inaccuracy as compared to those obtained using GA technique.

4.2 Illustration II

In this case the line is represented by a single pi section model. Figure 6 shows a single phase equivalent of a 132 kV, 120 km long transmission line. The line has series resistance of 9.6 Ω, series inductance of 0.1584 H, and total shunt capacitance of 1.44 μF (0.72 μF at each end) between the relay at one end and a fault on the other end.

Samples of voltage and current are generated by simulating this line model in PSCAD and applying a fault at time t = 1.0 s. The voltage and current waveforms are shown in Figure 7. Twenty samples were taken after applying the fault, with a sampling time interval of 0.001 s. These samples were used to find the value of R and L. In this

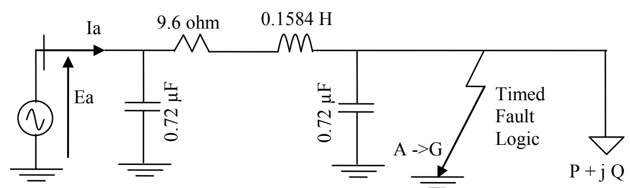

Figure 6. Single Pi section model of A faulted transmission line.

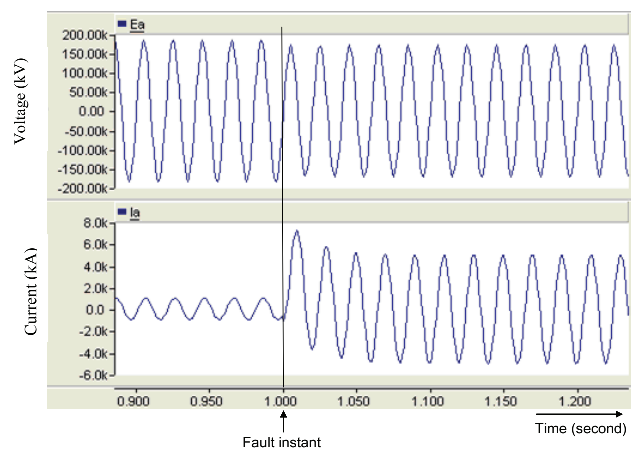

Figure 7. Pre and post fault voltage and current waveforms for pi section represented transmission line.

case shunt capacitance *C* is also a parameter, to be considered while performing the calculations and applying the algorithm. The best values of resistance and inductance are obtained by performing 40 generations (iterations) of GA. The results obtained using all the methods, GA, SDE, NLP, and MVS-LSQ, are shown in Table 2.

It can be seen that, in case of pi section representation also, the result obtained using GA are more accurate as compared to those using SDE, NLP, and MVS-LSQ techniques. In this case also the results presented in Table 2 (using SDE technique) are the average values. Further, in case of pi section representation of line, the coefficient matrix is invariably close to singular. This ill-conditioning (obtained using SDE technique) introduces large errors. The proposed GA based method is free from this source of error.

Table 2. Results obtained using different methods (Illustration II)

METHOD	ACTUAL VALUES: R = 6.4 Ω, L = 0.1056 H, |Z| = 33.7869 Ω, ∠ Z = 79.0809°							
	CALCULATED VALUES OF							
	R		L		|Z|		∠ Z	
	Value (Ω)	% error	Value (H)	% error	Value (Ω)	% error	Value (degrees)	% error
SDE	6.7457	5.4016	0.1083	2.5568	34.6857	2.6602	78.7856	0.3734
NLP	6.4887	4.5109	0.1083	2.5568	34.6367	2.5152	79.2026	0.1539
MVS-LSQ	6.4635	0.9922	0.1067	1.0417	34.1383	1.0400	79.0861	0.0066
GA	6.4685	1.0703	0.1057	0.0947	33.8308	0.1299	78.9771	0.1313

6. Conclusions

Differential equation algorithm based on SDE technique gives inaccurate location of fault (approximate values of *R* and *L*). This inaccuracy may be acceptable for a protective relaying decision, but is not acceptable for the purpose of locating the fault for inspection and repair. For this purpose the fault must be located with much higher accuracy. Investigations reported in this paper show that the GA approach, when coupled with SDE, has much to offer in this regard.

A GA based fault locator is presented in this paper, which uses the differential equation based algorithm. The problem of fault location is formulated as a unconstrained nonlinear optimization problem and is solved using GA technique. In GA technique the objective function is defined such that the error (difference in the measured value and calculated value of voltage at relay location) is minimized. To preempt any possibility of GA to converge to local optimum, uniform random number generator, has been successfully used in this paper. A comparison with the results obtained using conventional methods like SDE, NLP, and MVS-LSQ techniques shows that, starting with randomly generated population of *R* and *L*, GA zeros-in on to much more accurate values of *R* and *L*, than the conventional methods. Thus GA should find its place in the tool-kit of protection engineers.

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