Time Domain Fault Location on Transmission Lines Using Genetic Algorithm

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***Abstract*—This paper presents a new method for determining the fault location on two-terminal transmission lines using genetic algorithm. Distributed time-domain model of the transmission line is used to derive the fault location equations; therefore, impact of shunt capacitance of the line is fully considered. Synchronous post-fault voltage and current measurements from both sides of the line and the line parameters are used as the initial data for this method, while no assumption on the source impedance and fault type is made. Using the modal transformation, the presented method is applicable to both transposed and un-transposed lines and is independent of the fault type. By the use of time-domain model, the algorithm does not require filtering high frequency components and DC offset since these components are taken into account in the model. Evaluation studies based on EMTP/ATP simulation data demonstrate that the accuracy of the proposed algorithm is very high in different fault locations and fault resistances.**

Keywords- fault location, time domain, distributed model, Genetic Algorithm

I. INTRODUCTION

Transmission lines are vital links that achieve the essential continuity of service from the generating plants to the end users. Various events may threaten the effective role of overhead transmission lines such as lightning and short circuits, which may lead to transient or permanent faults on the lines. In case of permanent faults, it does not seem logical for the repair team to investigate whole-length of the line to find the exact fault location. Moreover, some permanent faults are not easily detected by human eye such as a crack in the insulator between overhead line and tower. Transient faults are mainly originated from the critical points in transmission lines such as polluted or insufficient insulation level, bird interference, etc. This kind of faults, although treated by reclosers, may deduce the useful lifetime of the reclosers and may be destructive for some factories. In this case, fault location will help to identify the critical points and take the necessary preventive maintenance operations. Thus, accurate fault location on transmission lines decreases the time needed for restoring the line and hence the restoration costs and increases the continuity of power transmission to end users.

Different techniques have been presented hitherto for fault location on transmission lines. These methods usually differ from each other in the following subjects:

- Transmission line model
- Number of terminals at which the voltages and/ or currents are measured and the type of measured variables
- The harmonic(s) and other frequencies used in the algorithm

Some algorithms use the fundamental frequency of the measured voltages and currents to calculate the impedance between the fault point and one of the terminals [1-3]. Then, knowing the impedance per unit-length of the line, the distance to the fault point is achieved. Although easily calculated, fault location in these algorithms is not very accurate since filtering or extracting the main harmonic from the measured data is not always precisely done. Moreover, they mostly use the lumped model of the transmission line.

Traveling wave has also been used for fault location in transmission lines [4, 5]. In this approach, knowing the velocity of the wave in the line, the traveling time of the post-fault created wave in the faulted line segment is used to calculate the fault location. One disadvantage of these methods is that they require using exact timing devices and accurate synchronization between two terminals.

Differential equations for transmission lines were first introduced in [6]. Using these equations, the time domain model of the transmission line is achieved and can be used for calculating the location of fault [7, 8]. The time domain approach for fault location does not need the fundamental harmonic of measurements as all harmonics and inter-harmonics have been taken into account in the model. The accurate distributed time domain model of transmission lines guarantees high accuracy of such methods.

In this paper, a fault location algorithm based on the distributed time domain model of transmission lines has been presented. The algorithm uses synchronous post-fault voltages and currents from both terminals.

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The fault location problem is converted to a minimization problem that its decision variable is the location of fault. Then, the solution to this optimization problem, i.e. the location of fault, is found using Genetic Algorithm.

This paper continues with description of the distributed model of transmission line used to derive the fault location equations. In the third part, the fault location algorithm is presented. Modal transformation which is used in the method is discussed in the fourth part, and the optimization method (GA) is described in the fifth part. The results of presented fault location method are presented in the sixth part. Finally, conclusion is made in the last part of the paper.

II. Distributed Model of Transmission Line

A single-phase diagram of a three-phase transmission line is presented in Fig. 1 in which S and R denote the sending and receiving ends and F shows the location of an arbitrary fault, respectively. Point F is located along the transmission line with a distance x from S terminal.

Distributed time domain model [6] of the SF segment is shown in Fig. 2. Following equations demonstrate the relation between voltages and currents at two ends of this section:

$$i_s(t) = \frac{1}{Z'_{s_{xs}}} u_s(t) + I_s(t - \tau_{xs}) \quad (1)$$

$$i_x(t) = \frac{1}{Z'_{s_{xs}}} u_x(t) + I_x(t - \tau_{xs}) \quad (2)$$

In the above equations, dependent current sources are defined as:

$$I_s(t - \tau_{xs}) = -\frac{\frac{R_{xs}}{4}}{{Z'_{s_{xs}}}^2}\left[u_s(t - \tau_{xs}) + Z''_{s_{xs}} i_s(t - \tau_{xs})\right] - \frac{Z_s}{{Z'_{s_{xs}}}^2}\left[u_x(t - \tau_{xs}) + Z''_{s_{xs}} i_x(t - \tau_{xs})\right] \quad (3)$$

$$I_x(t - \tau_{xs}) = -\frac{\frac{R_{xs}}{4}}{{Z'_{s_{xs}}}^2}\left[u_x(t - \tau_{xs}) + Z''_{s_{xs}} i_x(t - \tau_{xs})\right] - \frac{Z_s}{{Z'_{s_{xs}}}^2}\left[u_s(t - \tau_{xs}) + Z''_{s_{xs}} i_s(t - \tau_{xs})\right] \quad (4)$$

where:

Z_s surge impedance of the line

R_{xs} resistance of the SF segment

$Z'_{s_{xs}} = Z_s + \frac{R_{xs}}{4}$

$Z''_{s_{xs}} = Z_s - \frac{R_{xs}}{4}$

τ_{xs} time needed for the wave to travel from S to F

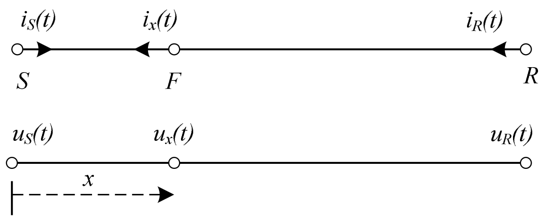

Figure 1. Single-phase diagram of a three-phase transmission line

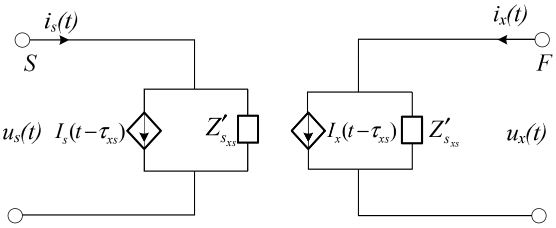

Figure 2. Distributed time domain model of SF segment

III. Fault Location Algorithm

Suppose a fault has occurred on the transmission line at point F in Fig. 2. Using equations (1) and (2), one can derive the voltage at fault point as a function of measured quantities at S terminal:

$$u_{xs}(t) = \frac{1}{2Z_s^2}\Big\{{Z'_{s_{xs}}}^2\left[u_s(t + \tau_{xs}) - Z'_{s_{xs}} i_s(t + \tau_{xs})\right] + {Z''_{s_{xs}}}^2\left[u_s(t - \tau_{xs}) + Z''_{s_{xs}} i_s(t - \tau_{xs})\right] - \frac{{R_{xs}}^2}{8} u_s(t) - \frac{R_{xs}}{2} Z'_{s_{xs}} Z''_{s_{xs}} i_s(t)\Big\} \quad (5)$$

With a similar approach, the voltage at the fault point can be expressed as a function of data measured at R terminal:

$$u_{xr}(t) = \frac{1}{2Z_s^2}\Big\{{Z'_{s_{xr}}}^2\left[u_r\big(t + (T - \tau_{xs})\big) - Z'_{s_{xr}} i_r\big(t + (T - \tau_{xs})\big)\right] + {Z''_{s_{xr}}}^2\left[u_r(t - (T - \tau_{xs})) + Z''_{s_{xr}} i_r(t - (T - \tau_{xs}))\right] - \frac{{R_{xr}}^2}{8} u_r(t) - \frac{R_{xr}}{2} Z'_{s_{xr}} Z''_{s_{xr}} i_r(t)\Big\} \quad (6)$$

where:

R_{xr} resistance of the RF segment

$Z'_{s_{xr}} = Z_s + \frac{R_{xr}}{4}$

$Z''_{s_{xr}} = Z_s - \frac{R_{xr}}{4}$

T time needed for the wave to travel from S to R

Since the voltage of the fault point should be unique regardless of the data used for calculating it, the two derived voltages, i.e. $u_{xs}(t)$and $u_{xr}(t)$should be equal at all sampling moments. Therefore, the following equation should be held in the actual fault point (F) at all moments:

$$F(u_s, i_s, u_r, i_r, t, \tau_{xs}) = u_{xs}(t) - u_{xr}(t) = 0 \tag{7}$$

The distance from S terminal to the fault point, x, is not explicitly seen in (7) and is hidden in the surge traveling time,τ_{xs}. Moreover, this traveling time does not appear as a variable in this equation and is a value on which the voltages and currents depend.

Note that voltages and currents are measured at discrete moments at terminals of the transmission line and are quantized; hence, the equations used in the method should also be discretized. Therefore, (7) is first discretized and then the following optimization problem is solved:

$$Min\ obj(n_{xs}) = \underset{n_{xs}}{Min} \sum_{k=n_{xs}}^{N-n_{xs}} F^2(n_{xs}, k) \tag{8}$$

where:

n_{xs} $= \dfrac{\tau_{xs}}{\Delta t}$

k $= \dfrac{t}{\Delta t}$

N total samples

Δt sampling time

n_{xs}, k arbitrary integers

The unknown location of fault is achieved by minimizing the defined objective function. In more details, at first the value of the following equation is calculated for each arbitrary location of fault:

$$\sum_k F^2(k) = \sum_k [u_{xs}(k) - u_{xr}(k)]^2 \tag{9}$$

At the actual location of fault, the value of (9) should be at its minimum; therefore, this value should be calculated for all possible locations of fault along the transmission line. The supposed location of fault which has the minimum value of (9) among other locations is selected as the actual fault location.

In the proposed method, the objective function is minimized using GA, which will be described later in the fifth part of the paper.

IV. Modal transformation

The governing equations in three-phase transmission lines are a group of coupled equations since the lines mutually affect each other. In transposed transmission lines, symmetrical component transformation is used to eliminate these mutual effects in steady state equations. A similar trend for un-transposed transmission lines is using the modal transformation [6]. Modal transformation is essentially characterized with the ability to decompose a certain group of coupled equations into decoupled ones excluding the mutual parts among these equations. Thus, each equation in the modal domain is behaved like the equation for a single-phase transmission line. The modal transformation, unlike the symmetrical component transformation, can be used for the transient studies and is hence applicable to time domain model equations. A commonly used modal transformation matrix is defined as [6]:

$$M = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix} \tag{10}$$

Using this matrix, the phase quantities can be transformed to each other as:

$$[I_{Ph}] = M \times [I_M] \tag{11}$$

$$[I_M] = M^{-1} \times [I_{Ph}] \tag{12}$$

From the above equations, we have:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{13}$$

I_0 is called the ground mode current and I_1 and I_2 are the aerial modes. As the aerial modes have non-zero values in all fault types, aerial mode 1 has been used in the fault location procedure. In a similar trend, phase voltages could be transformed into modal voltages.

After applying the modal transformation to the voltage and current waveforms at both terminals, the system equations are decoupled and the first aerial mode is used for fault location in the three-phase transmission line.

V. Genetic Algorithm

Genetic Algorithms (GAs) are a family of computational models inspired from the evolution theorem. The algorithm encodes the assumed solution to the problem on a simple chromosome-like data structure. The GA starts with generating an initial population of typically random chromosomes. Then at each step, applying recombination operators, GA uses the current population to create the children that make up the next generation. The GA evaluates these structures and allocates reproductive opportunities such that those chromosomes which represent a better solution to the problem are given more chances to reproduce than those chromosomes which are poorer solutions. After several generations are created, the GA typically moves to the optimum solution.

As described above, GA randomly generates many individual solutions at first. The population size depends on the nature of the problem, but typically contains several possible solutions. In this paper, population contains 20 different solutions, i.e. 20 different chromosomes. The location of fault should never be negative or more than 300^{km}; therefore, each

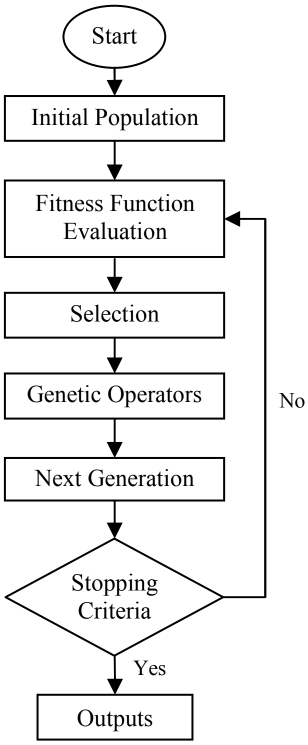

Figure 3. GA methodology

member of the population is constrained between these thresholds.

More detail of GA methodology is depicted in Fig. 3. After producing the random initial generation, fitness function is evaluated for each chromosome. In this paper, (8) is selected as the fitness function. The chromosomes that have better values of fitness function (less value of (8)) are selected as the parents for the next generation. Then, applying genetic operators such as "Crossover" and "Mutation", next generation is achieved. GA now checks the stopping criteria. In this paper, number of total generations has been chosen as the stopping criterion. The next step would be repeating the procedure from the beginning if the criterion is not satisfied, as seen in Fig. 3. On the other hand, the algorithm stops when 300 generations have been produced. Finally, the chromosome that has provided the best (minimum) value of the fitness function among the chromosomes created in all generations is presented as the best solution to the problem. More detail of GA is available in [9]; however, it is worth noting that crossover and mutation probability in this paper are selected 0.7 and 0.1, respectively.

VI. TEST RESULTS

Performance of the proposed algorithm is evaluated in this section. Fig. 4 shows a three-phase 400^{kV} transmission line with a length of 300^{km} and the parameters shown in table I. A fault occurs at an arbitrary point F at a distance x from sending end (S terminal). The measurements are extracted from the ATP/EMTP software and imported to the Genetic Algorithm Toolbox of MATLAB.

TABLE I. TRANSMISSION LINE PARAMETERS

$R^{+}_{line} = 0.0275\frac{\Omega}{km}$	$R^{0}_{line} = 0.275\frac{\Omega}{km}$
$L^{+}_{line} = 1.00268\frac{mH}{km}$	$L^{0}_{line} = 3.26798\frac{mH}{km}$
$C^{+}_{line} = 0.013\frac{\mu F}{km}$	$C^{0}_{line} = 0.0085\frac{\mu F}{km}$

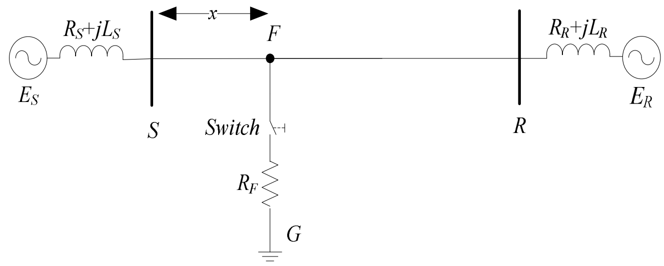

Figure 4. Case study system

The minimization approach would seem clearer with a plot of objective function (8) in Fig. 5. In this figure, the value of objective function has been shown in different hypothetical locations of fault when a solid three-phase balanced fault has occurred on the transmission line at 100^{km} from S terminal. A glance on Fig. 5 reveals that the objective function has its minimum value at somewhere near 100^{km}, which is the actual location of fault. As described earlier, GA has been used in this paper to find the value of the decision variable at which the objective function is minimized.

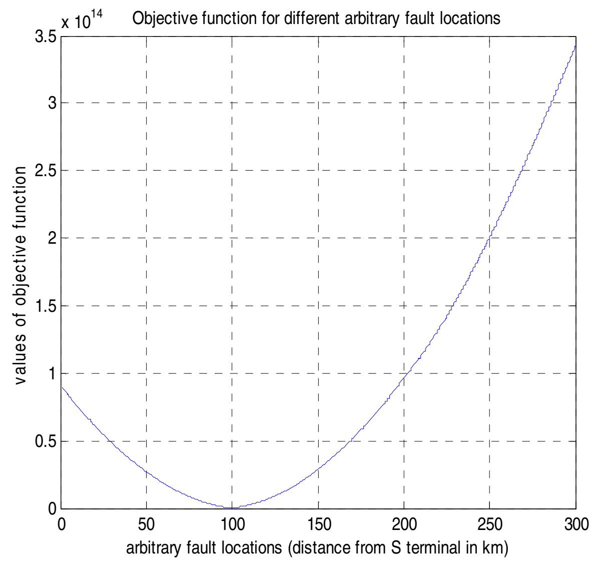

Figure 5. Objective function for different arbitrary fault locations for the actual fault happening at 100^{km} from S terminal

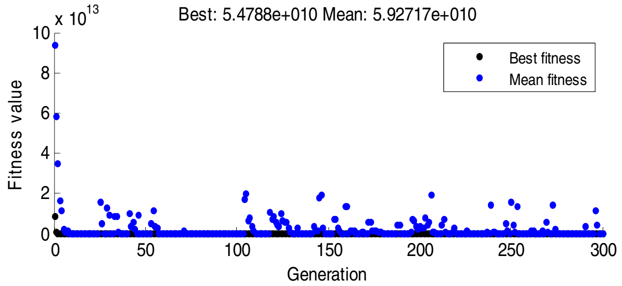

Figure 6. GA results for fault happening at 100^{km} from S terminal

The evolution process of GA for the special case stated for Fig. 5 is depicted in Fig. 6. As seen in this figure, the generations created by GA gradually move to the better values of fitness function. In the cited location and type of fault, GA presents the distance of fault from S terminal to be 99.882^{km}, which is very close to the actual fault point.

The accuracy of the proposed fault location method has been analyzed for both balanced and unbalanced faults in different fault locations and the percentage of error, calculated as (14), is presented in table II.

$$\%error = \frac{x_{calculated} - x_{actual}}{L_{sr}} \times 100 \tag{14}$$

where:

$x_{calculated}$ calculated fault location

x_{actual} actual fault location

L_{sr} total length of the line

The results show high accuracy of the algorithm for locating faults on a transmission line regardless of the fault type and fault resistance. The algorithm does not need the source parameters at line terminals and fault type as an initial data and acquires exact results for the fault location.

VII. CONCLUSION

In this paper, an accurate fault location method for two terminal transmission lines based on the distributed time-domain model of the lines has been proposed. The presented method uses synchronous post-fault voltage and current samples at both terminals and does not need the type of fault and source parameters at the terminals as an initial data. The Genetic Algorithm has been used to minimize the objective function, yielding the location of fault.

The method does not need filtering the DC offset and high frequency transients and its accuracy is high in different fault resistances. Impact of shunt capacitance of the line is fully considered in the applied model of transmission line. Furthermore, the presented method is applicable to both transposed and un-transposed lines. The accuracy of the proposed method has been analyzed for different fault types and fault locations. The presented results show high accuracy of the method.

TABLE II. PERCENTAGE OF ERROR OF FAULT LOCATION

Fault Type	Fault Res. (Ohms)	Actual Fault Location (distance from S terminal in km)								
		5	25	50	100	150	200	250	275	295
		Percentage of Error of Fault Location								
ABCG	0	0.0418	0.0327	0.0088	-0.0392	-0.0871	-0.1350	-0.1349	0.0412	0.0510
	1	0.0637	0.0327	0.0088	-0.0392	-0.0871	-0.1350	-0.1475	0.0575	0.0510
	10	-0.0509	0.0327	0.0088	-0.0392	-0.0870	0.1520	-0.1829	0.1083	0.0509
	50	-0.0509	0.0327	0.0087	-0.0392	-0.0871	0.0392	-0.0087	-0.0103	0.0510
AG	0	0.0055	0.0327	0.0087	-0.0392	-0.0871	-0.1350	0.1842	0.1323	0.0509
	1	0.0483	0.0327	0.0087	-0.0392	-0.0870	-0.1350	0.2062	0.1527	0.0509
	10	0.2334	0.0327	0.0087	-0.0392	-0.0870	0.3266	0.2787	0.2547	0.0509
	50	0.1451	0.0327	0.0087	-0.0392	-0.0871	0.3266	0.2787	0.2547	0.0509
ABG	0	0.0418	0.0329	0.0088	-0.0392	-0.0871	-0.1350	-0.1267	0.0408	0.0272
	1	0.0384	0.0329	0.0088	-0.0392	-0.0871	-0.1350	0.0469	0.0388	0.0502
	10	0.0384	0.0332	0.0088	-0.0391	-0.0871	-0.1350	0.0469	0.0388	0.0394
	50	0.0409	0.0329	0.0088	-0.0392	-0.0871	-0.1350	0.0469	0.0388	0.0058
AB	0	0.0389	0.0334	0.0088	-0.0392	-0.0871	-0.1350	0.0466	0.0384	0.0494
	1	0.4107	0.2069	0.1829	0.1350	-0.0871	-0.1350	-0.0088	-0.0327	-0.2365
	5	0.4107	0.2069	0.1829	0.1350	-0.0871	-0.1350	-0.0088	-0.0327	-0.2365

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