

A New Whale Optimization Algorithm-Based Fault Location Method by Focusing on Dispersed Model of the Transmission Line

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In this paper, a fault location approach is presented by using the Whale Optimization Algorithm (WOA) strategy in two terminal transmission feeders. Also, the Grey Wolf Optimization (GWO) method is discussed. Voltage and current are measured in both ends to collect the data required for the proposed strategy. The paper considers several types of faults and simulations, and the objective function identifies the fault location with a high accuracy in a short time. In addition, based on distributed model of the line, the fault location is defined and the optimization algorithm does not utilize the compressed model of the line, and the calculations are highly accurate. The WOA-based optimization method results in a notable reduction in the computational time. As the benefit of the proposed technique, accurate and timely location of the source of the fault is highly helpful to the repair crew. Almost in all cases, the accuracy of the proposed procedure is very high, and the error is kept below 1%.

Article Info

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I. INTRODUCTION

Basic goal of power system is to continuously provide electrical energy to the users. Like any other system, failures may occur in a power system. After detecting fault condition and location, it is critical to apply correct remedial actions. Accurate determination of fault location and its condition are important. Since the visual search of faulted lines are costly and sometimes inconclusive, fast and precise designation of fault location is necessary for prompt restoration of power, particularly on transmission lines, which would lead to saving on time and resources for the electric utilities. This will help field personnel to figure out the fault locations from transmission line maps and drawings. As a result, power

system operators can identify and isolate faulted sections by opening circuit breakers or switches correctly and timely.

Subsequently, the power is restored to healthy transmission sections, and the customers are supplied reliably because long outages on the customer side are prevented and quick detection of faults helps beneficiaries to tackle them as fast as possible. It is worth noting that to increase the accuracy of calculations, line modeling plays a key role in the fault location process. Using distributed model of the line is one of the prevalent approaches in fault location optimization problems. Various methods have been proposed in the literature and have extensively been used to improve the solution of an optimal fault location problem. Linear programming (LP), nonlinear programming (NLP) mixed nonlinear techniques are just some examples. These methods have been classified and their advantages, limitations and requirements have been discussed in detail. One essential aspect of these methods is how to model the transmission line because it changes the accuracy of the calculations. Some

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researches have focused on modeling lines with a compressed model, which reduces the accuracy of the calculations. So, to improve the precision of calculations, it is inevitable to use more comprehensive models of the transmission line. One of these accurate models is the distributed model of lines. According to the distributed time domain model of the lines, Ghiafeh Davoudi and Sadeh [1] proposed a method to detect the fault location using post-fault voltage and current samples at both terminals in which the objective was minimized by the genetic algorithm. Kezunovic and Mrkic [2] introduced a new fault location method based on the information of two end systems. It considers two different algorithm constructions utilizing two line models, and simulation performance is achieved by using EMTP software. It uses time sampling method for the proposed approach and it is concluded as the proposed method is cost-effective. Also, an algorithm is introduced by Sadeh [3] that uses time domain line model which is compensated with series connected FACTS device. It improves accuracy. An application of this technique can be developed to any series FACTS compensated line. Due to the calculation of the location and resistance of the fault, samples of voltage and current at both ends of the line are used synchronously. Ghazizadeh [4] suggested a novel arcing faults location technique for multi-segment combined transmission lines, which uses unsynchronized measurements from two terminals of the line. Also, Junzhang and Zhonghui [5] showed that fault location accuracy has been reduced by ignoring the line distributed capacitance. In document Ahmed and Attia [6], some optimization algorithms like teaching-learning-based optimization and harmony search algorithms are used. Also, some methods such as genetic algorithm, artificial bee colony, artificial neural networks and cause and effect are discussed along with the advantages and disadvantages of all methods. In Youssef [7], an accurate method is discussed about the calculations needed to find the exact fault location on transmission lines. It used travelling wave-based method. The method is unaffected by noise or spurious changes in line. Salehi [8] presents a closed-form solution for fault location that does not need the GPS-synchronized sampling of wide-area measurements. Sparse intelligence is used to record the unsynchronized measurement. Also, the Schur-Banachiewicz inversion formula is utilized to obtain a solution for fault location.

From the previous efforts, we can conclude that these approaches have many contrasts, especially as to points such as the model of transmission line, measured variables from one side or both sides, and the optimization strategies employed to get the best results. Since the fault location is not derived directly from equations related to the currents and voltages, more smart methods are used to detect fault location in transmission systems.

Based on the goal, the present paper focuses on the operational use and application of a pre-existing approach, which has been already described in the literature. In this paper, some structures like the model of the transmission line, optimization algorithm, and cost function are updated and all information about the model used in locating the fault are fully described. Here, our approach to find the fault location is as follows. First, the objective function along time interval is defined. Second, to perform the fault location (FL) calculations, samples of currents and voltages are taken. Then, the optimal solution of the problem is found. We also vary the accurate fault location to measure the advantages of the proposed approach. The results are compared with the results obtained by the GWO algorithm. The main objective of this paper is to find out the best solution for the problem using WOA. The results show that by using a distributed model of the line and information which are sent from PMUs, under the dynamic operation, online employment of the approach is feasible. In this paper, we calculate the location of different types of faults in the category shown in Fig. 1.

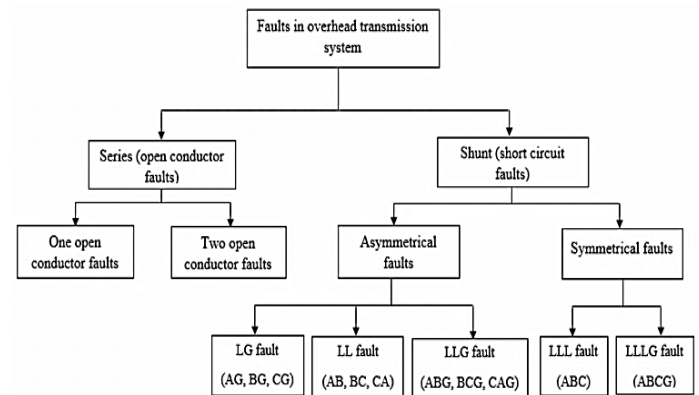


Fig. 1. Classification of faults.

II. DISPERSED MODEL OF TRANSMISSION LINE

A single-phase diagram of a three-phase transmission line with distributed parameters is shown in Fig. 2 where S and R denote the sending and receiving ends, respectively, and F shows the location of a free fault. Point F with a distance x from S end is located along the transmission line. As a rule, lumped RLC elements are usually utilized for short transmission lines whereas the dispersed model is for long lines [9]. To select an appropriate transmission line model, a decision is made based on a tree shown in Fig. 3 where traveling time is equal to length of line/speed of light and Δt is the solution time step.

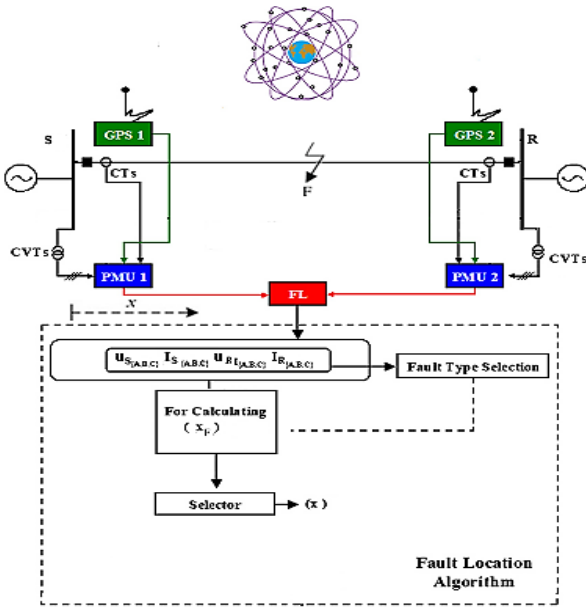


Fig. 2. A single-line diagram of the transmission line.

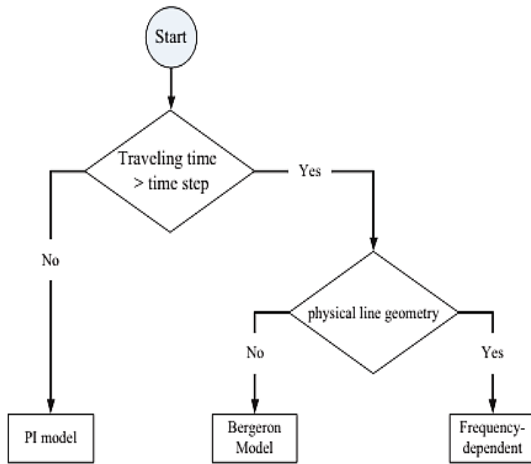


Fig. 3. The decision tree for selecting the transmission line model [16].

A distributed model of transmission line (segments S to F) is shown in Figs. 4-5. A set of equations depict the relevance between voltages and currents to send and receive end buses as follows (Bergeron's equations) [9; 10]:

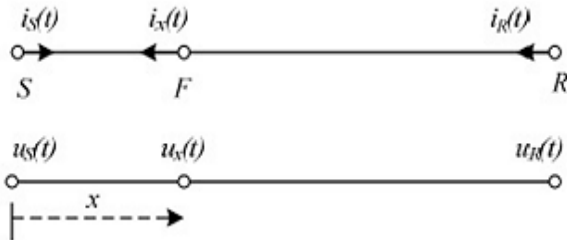


Fig. 4. The single phase diagram of a three-phase transmission line.

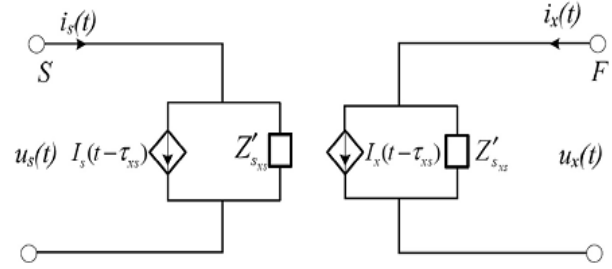


Fig. 5. The distributed model of the transmission line (segments S to F).

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

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

where the dependent source currents can be described by Eq. (3)- (4).

$$I_s(t - \tau_{xs}) = \frac{R_{xs}}{Z'_{sxs}} \frac{4}{2} u_s(t - \tau_{xs}) + Z''_{sxs} i_s(t - \tau_{xs}) - \quad (3)$$

$$I_x(t - \tau_{xs}) = \frac{R_{xs}}{Z'_{sxs}} \frac{4}{2} u_x(t - \tau_{xs}) + Z''_{sxs} i_x(t - \tau_{xs}) - \quad (4)$$

$$- \frac{Z_s}{Z'_{sxs}} \frac{4}{2} u_s(t - \tau_{xs}) + Z''_{sxs} i_s(t - \tau_{xs})$$

where Z_s is the surge impedance of the line and R_{xs} is the resistance of the SF section.

$$Z'_{sxs} = Z_s + \frac{R_{xs}}{4} \quad (5)$$

$$Z''_{sxs} = Z_s - \frac{R_{xs}}{4} \quad (6)$$

Where τ_{xs} is the time required for the wave to traverse from S to F.

T is the time required for the wave to traverse from S to R. In a single-phase Bergeron transmission line of two buses, if the fault takes place at point F, from above equation we can conclude that as a function of measured quantities at terminals S and R, the voltage at fault point can be extracted

where R_{xr} is the resistance of the RF section.

$$Z'_{sxr} = Z_s + \frac{R_{xr}}{4} \quad (7)$$

$$Z''_{sxr} = Z_s - \frac{R_{xr}}{4} \quad (8)$$

The part of transmission line from receive end to fault (F) point is named RF section. At the fault point, the voltage can be calculated using the quantities measured at terminals S and R. The following equations describe it.

$$u_{XS}(t) = \left\{ \frac{1}{2Z_s^2} Z_{SXS}^2 [u_S(t + \tau_{XS}) - Z_{SXS}' i_S(t + \tau_{XS})] \right. \\ \left. + Z_{SXS}'^2 [u_S(t - \tau_{XS}) - Z_{SXS}'' i_S(t - \tau_{XS})] \right. \\ \left. - \frac{R_{XS}^2}{8} u_S(t) - \frac{R_{XS}}{2} Z_{SXS}' Z_{SXS}'' i_S(t) \right\} \quad (9)$$

$$u_{XR}(t) = \left\{ -\frac{1}{2Z_s^2} Z_{SXR}^2 [u_R(t + (T - \tau_{XS})) - Z_{SXR}' i_R(t + (T - \tau_{XS}))] \right. \\ \left. + Z_{SXR}''^2 [u_R(t - (T - \tau_{XS})) + Z_{SXR}' i_R(t - (T - \tau_{XS}))] \right. \\ \left. - \frac{R_{XS}^2}{8} u_R(t) - \frac{R_{XR}}{2} Z_{SXR}' Z_{SXR}'' i_R(t) \right\} \quad (10)$$

Based on the Bergeron model, the distributed parameters are characterized by the surge impedance and phase velocity. In this study, we can define the objective function based on the fact that, at fault point, voltage is the same as whatever calculated from sending or receiving end.

III. OPTIMAL FAULT LOCATION APPROACH

This section formulates an optimization model to determine the solution of fault location problem. To get the solution of the optimization problem, it is necessary to determine an objective function which deals with decision variable. The goal is to obtain the distance between fault point and sending end. It is necessary to use an optimization technique to solve the fault allocation problem in such a way that the objective function is minimized. The formulation of the objective function is based on the voltage difference, considering n_{XS} and k as discrete variable.

A. Objective Function

The objective function is based on partial differential equations of the transmission line model which has two variables: : position and time. By placing the measured voltage and current as boundary conditions in those functions, fault location can be calculated. To find the fault location, the key idea of this work is based on minimizing the voltage differential at fault point.

1) Minimization of Voltage differential at Fault Point

With the measured quantities at S and R terminals and using Eq. (1) and (2), we can conclude the following equation. Since the voltage of the fault point should be singular, the voltage differential at point F should be held at zero.

$$F(us, is, ur, ir, t, \tau_{XS}) = |u_{XS}(t, \tau_{XS}) - u_{XR}(t, \tau_{XS})| \quad (11)$$

Eq. (11) must be reached to its least value. It should be noted that the discretization of the measured voltage and current at discrete moments must be considered.

$$F(k, x) = |u_{XS}(k, x) - u_{XR}(k, x)| \quad (12)$$

The fault point X_F is estimated by scanning the minimum value of the absolute difference between the fault voltage seen by both end. The scanning of $F(k, x)$ for each Δt starts at $t_{Start} = K_0 \Delta t$ and proceeds until the protection system pick-up at $t_{Stop} = K_1 \Delta t$.

The mean value over time of $F(k, x)$ leads to a better understanding of fault voltage behavior during the whole fault period. Its calculation is as follows:

$$\text{Min (obj)} = \min \left(\frac{1}{\Delta t(k_1 - k_0)} \sum_{k=k_0}^{k=k_1} F(k, x) \right) \quad (13)$$

$$k = \frac{t}{\Delta t} \quad (14)$$

$$n_{XS} = \frac{\tau_{XS}}{\Delta t} \quad (15)$$

$$x = C \times \tau_{XS} \quad (16)$$

$$C = 3 \times 10^8 \text{ m/s}$$

Δt : Sampling step.

n_{XS} , k arbitrary integers.

In this paper, the objective function is set at its minimum value using the WOA and GWO algorithms and the results are compared with each other. These algorithms are described in Section 5.

2) Constraint

In this paper, the inequality constraint for distance, x , is given by Eq. (17) in which x is the distance from sending end to the fault point.

$$0 \leq x \leq L \quad (17)$$

IV. MODAL TRANSFORMATION

The coupled direct equations in the three-phase transmission line are as below:

$$\frac{\partial v(x, t)}{\partial x} = -L \frac{\partial i(x, t)}{\partial t} \quad (18)$$

$$\frac{\partial i(x, t)}{\partial x} = -C \frac{\partial v(x, t)}{\partial t} \quad (19)$$

To get rid of the mutual effects, a transformation should be used to eliminate the foresaid mutual effects. Modal transformation can decompose the coupled equations into decoupled ones. By determining the equation in modal domain that is similar to the equation for a single-phase transmission line, decoupling process is terminated. A commonly used modal transformation matrix is defined as:

$$M = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix} \quad (20)$$

The phase quantities will be transformed to each other by using M matrix.

$$[I_{ph}] = M \times [I_M] \quad (21)$$

$$[I_M] = M^{-1} \times [I_{ph}] \quad (22)$$

Eq. (23) can be extracted by Eq. (22).

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (23)$$

in which I_0 is ground mode current and I_1 and I_2 are the aerial mode. Aerial mode 1 will be used in the fault location procedure if the aerial modes have non-zero values in all fault types. Similarly, the voltages can be derived in modal domain. The equations governing the system were derived based on these equations, and finally, the first aerial mode is used to determine the fault location in three phase transmission line. In this paper, since fault location is determined by minimizing the objective function, two different optimization algorithms are considered. The objective function is defined in Eq. (13). To assess fault location, there is a need to use an optimization algorithm with some features such as having fewer control parameters and shorter computational time, being simple and fast to converge, and having an ability to explore wider search area. In the present work, the WOA and GWO algorithms are initially used to optimally locate the fault. The use of these algorithms is based on the following reasons. First, the algorithm is universal for problem-solving and does not need to transform the problem as a linear and mix-integer model. Second, we define some constraints to the problem. These algorithms are swarm-based methods which are driven from the collective behavior of social creatures. The implementation of swarm-based algorithms is easier than the evolutionary-based algorithms because they include fewer operators (i.e., selection, crossover, mutation). Also, these algorithms have lower input parameters as compared to evolutionary-based algorithms, like genetic algorithm. These methods use time domain representation of the signal and distributed-parameter model of the transmission line. Two approaches solve partial equations using optimization algorithm methods. They require the solution of partial differential equations.

A. Whale Optimization Algorithm (WOA)

In 2016, Mirjalili and Lewis developed an optimization algorithm which named Whale Optimization Algorithm (WOA). It is inspired by the hunting behavior of humpback whales in response to the search for food in the nature [11]. The main interesting point of these whales is how they hunt humpbacks. In WOA, each solution is thought to be a whale. In this solution, a whale tries to replete a new place in the search space considered as a reference the best element of the group. Two mechanisms are used by the whales to locate their prey and attack it. In the first one, the preys are encircled and the second creates bubble nets. Regarding optimization, when the whales look for a prey, the search space is explored and the exploitation occurs during the attack behavior. Random search and local search are two main characteristics of WOA. They play an important role to get the highest capability in solving the optimization problem. WOA has some good features, like simplicity, reliability, robustness, and

flexibility. As already mentioned, the operational steps of this algorithm include the following ones: encircling the target, bubble-net attacking method, and searching for the target. Ashraf Darwish [12] and Xiaofei Wang and Hui Zhao [13] have described it in details.

B. Grey wolf Optimization (GWO)

The GWO algorithm is one of the recent meta-heuristic algorithms which is based on hunting and social leadership of grey wolves (Ashraf Darwish [12]). It was proposed by Iranian scholar Mirjalili in 2014. Gray wolves usually live in groups, and under the leadership of a head grey wolf, the wolves capture the prey through a series of processes, such as surrounding, hunting and attacking. In this algorithm, attaining the results is centered on three best grey wolves. The leader of the group is called alpha and is responsible for some activities such as making decisions about sleeping place and hunting [12, 13]. The second wolf is called beta, and he helps the wolf alpha in making decisions. The third grey wolf is called omega and is responsible for providing information to all the other wolves. All the other remaining gray wolves are called delta. They are responsible for dominating the omega. The main phases of the GWO algorithm are based on the following steps [12]:

- Tracking, chasing and approaching the prey.
- Pursuing, encircling and harassing the prey.
- Attacking the prey.

More details on this algorithm is available in [13]. In this paper the performance of our approach is evaluated by the GWO algorithm.

C. Flowchart

More details about the proposed approach is depicted in Fig. 6. In this paper, Eq. (13) is selected as the fitness function.

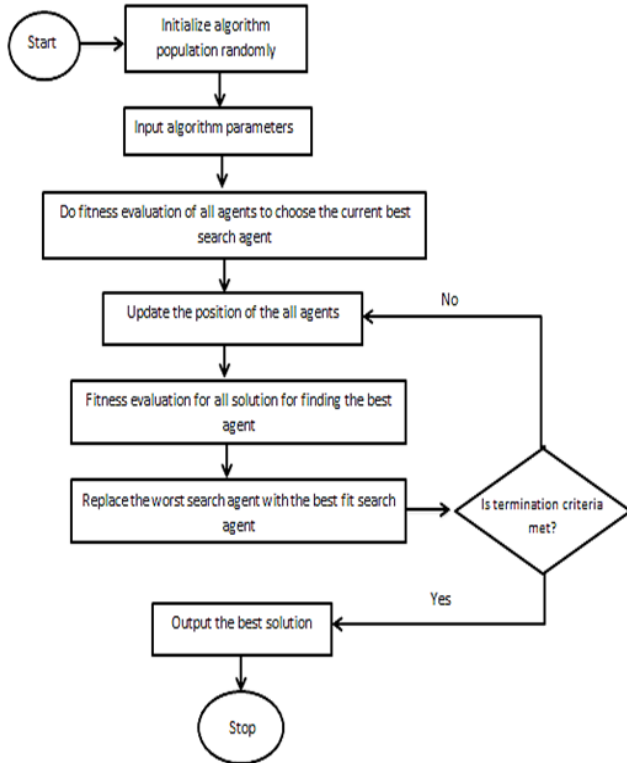


Fig. 6. The WOA methodology.

It is shown that in the optimization procedure, whenever the initial solutions are generated, the fitness function is evaluated for each solution. The solution that has the best fitness function (lower value of Eq. (13)) is used to update the current solutions. This step is repeated until the breaking rule is met. Finally, among all the solutions, the one with the best value of the fitness function is selected as the optimum solution of the problem

V. SIMULATED CASE STUDY

In order to get the exact fault location, two different optimization algorithms are considered in this paper. It should be noted that there is an effective factor for any method to attain the location of the fault. This is mis-locality in the consequences, which is defined by Eq. (24).

$$E_{FL} = \frac{X_{measured} - X_{real}}{L_{sr}} \times 100 \quad (24)$$

where $X_{measured}$ is the measured location of a fault, X_{real} is the real location of the fault, and L_{sr} is the totality of line length. This equation provides a metric to analyze the accuracy of the proposed fault location methods.

VI. RESULTS AND DISCUSSION

A series of simulation studies were conducted to evaluate the performance of the approach using MATLAB/Simulink. The test system is shown in Fig. 7. The voltage of the system was 400 kV and the length of line was 120 km. The variables

of this line are presented in Table 1. A fault occurs at point F with an distance of X km from the end bus (S) after the simulating results are obtained. Optimization would be done by using the WOA and GWO algorithms. The maximum number of iterations and initial population size were set at 500 and 100, respectively. In order to avoid the fluctuations of the performance, we repeated the algorithm for 20 times. After finding the voltage and current waveforms in the modal domain, optimization algorithm was utilized to locate the fault. The results were illustrated for comparison. A three-phase fault to ground has occurred on section SR without any resistance to ground.

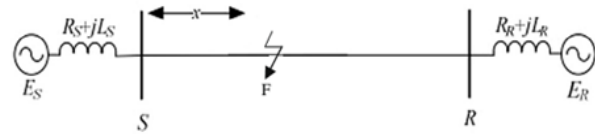


Fig. 7. The studied system.

TABLE I
TRANSMISSION LINE PARAMETERS

$R^+_{Line} = 0.0275 \quad \Omega/km$	$R^0_{Line} = 0.0275 \quad \Omega/km$
$L^+_{Line} = 1.00268 \quad mH/km$	$L^0_{Line} = 3.26798 \quad mH/km$
$C^+_{Line} = 0.013 \quad \mu F/km$	$C^0_{Line} = 0.0085 \quad \mu F/km$

The fault occurrence time was 0.02 s and its clearance time was .04 s. The voltage and current waveforms were achieved at buses S and R as shown in Figs. 9-12, respectively. Also, their adaptive waveforms in the modal domain are depicted in Figs. 13-16. These figures illustrate the voltage and current change during the time interval between 0-2 s. The average operation time of the WOA and GWO algorithms were 10.125 min and 1.957 min, respectively. So, based on the time value to achieve the result for all types, WOA took more time to optimize the objective function. It may be regarded as a bad attainment. A comparison between WOA and GWO was done to verifying which algorithm was better than the other.

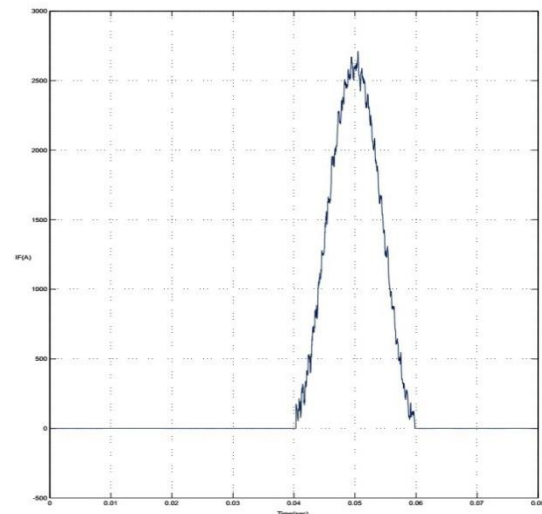


Fig. 8. The fault current waveform.

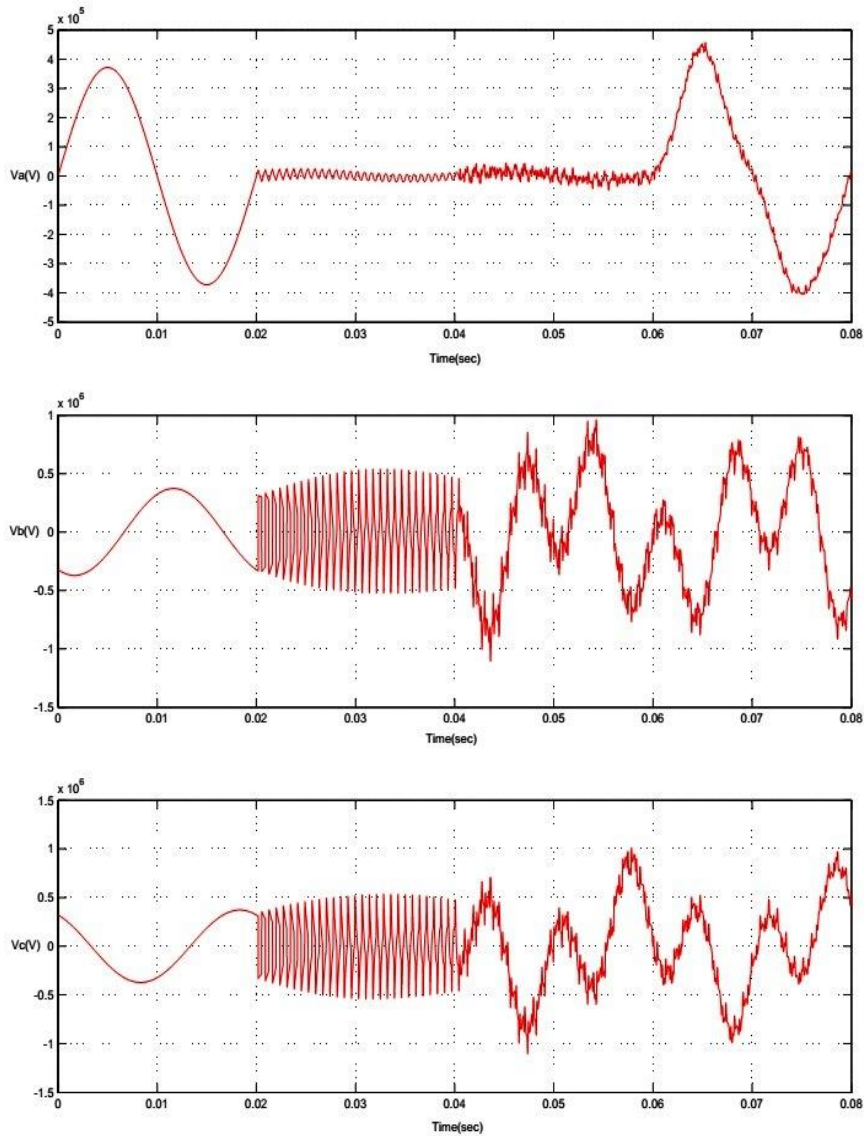


Fig. 9. Three-phase voltage waveforms of terminal S.

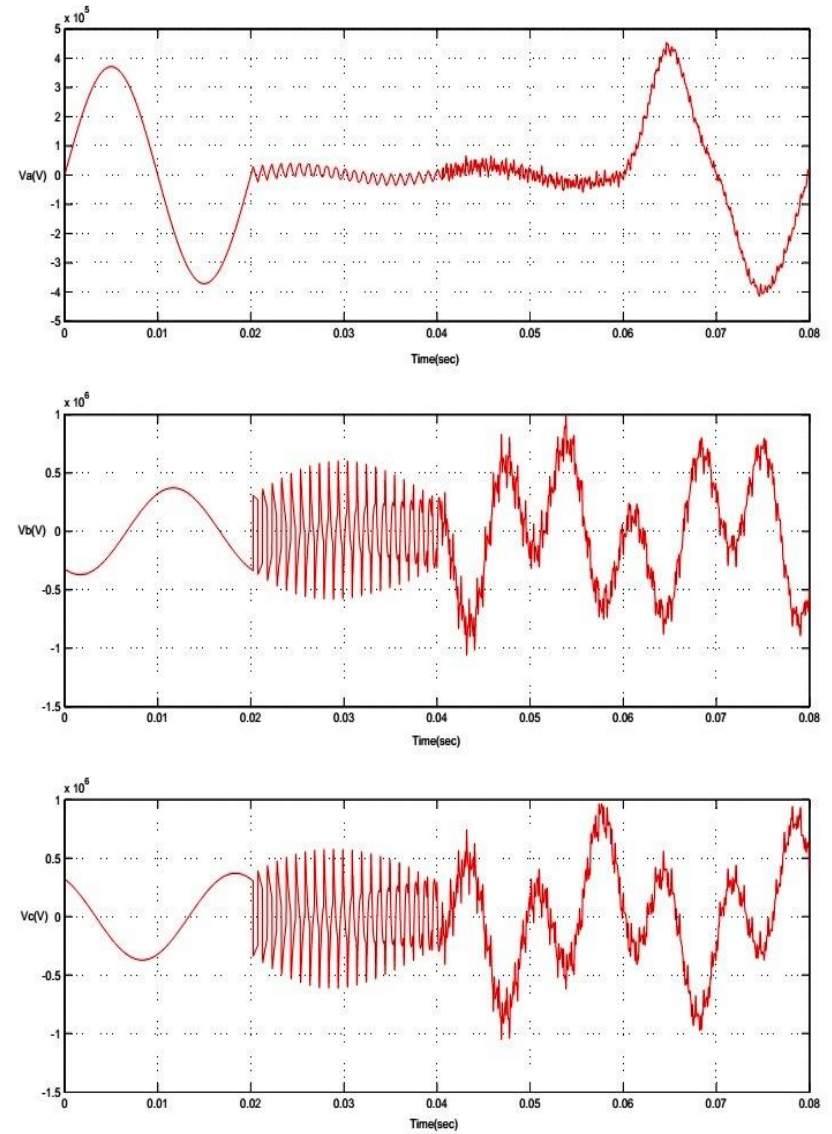


Fig. 10. Three-phase voltage waveforms of terminal R.

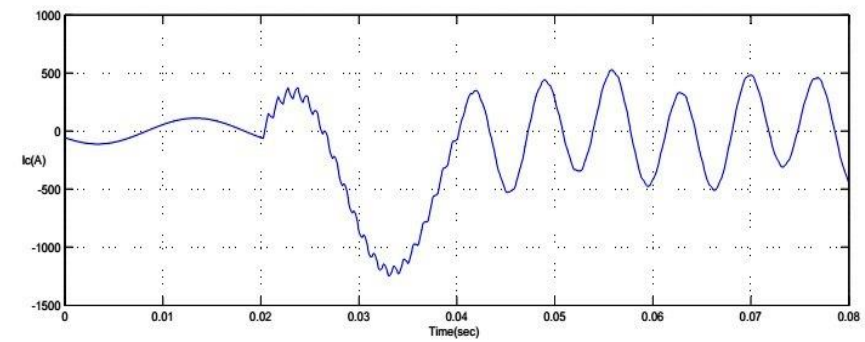
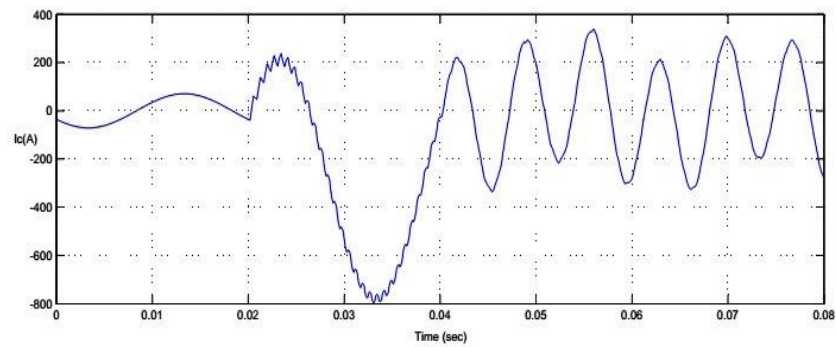
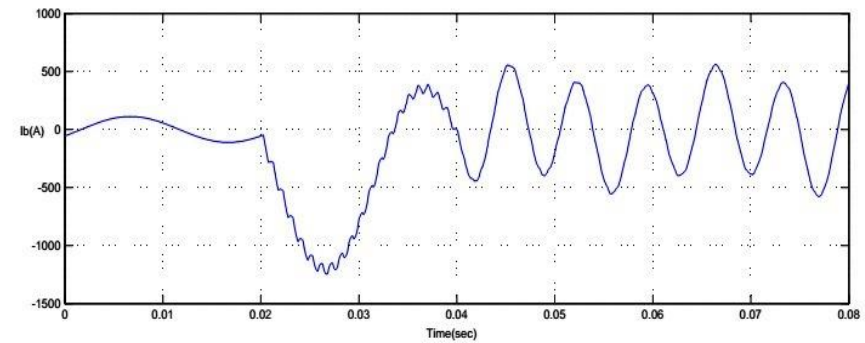
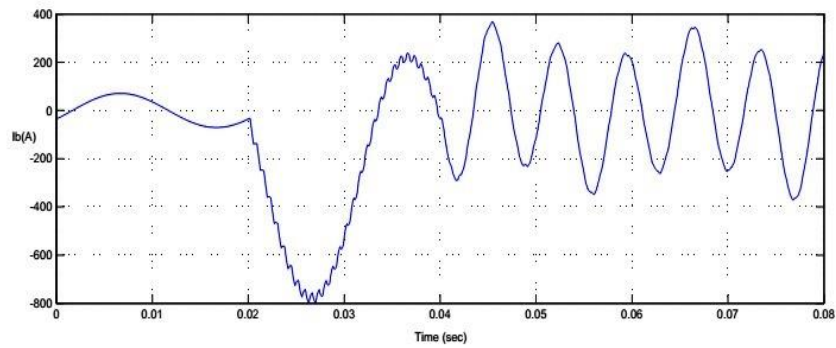
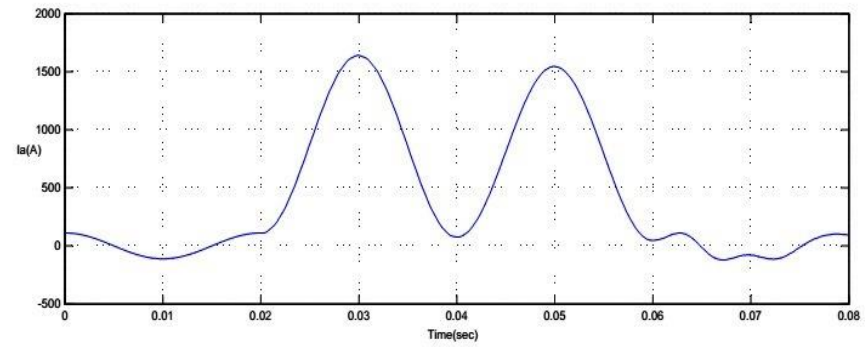
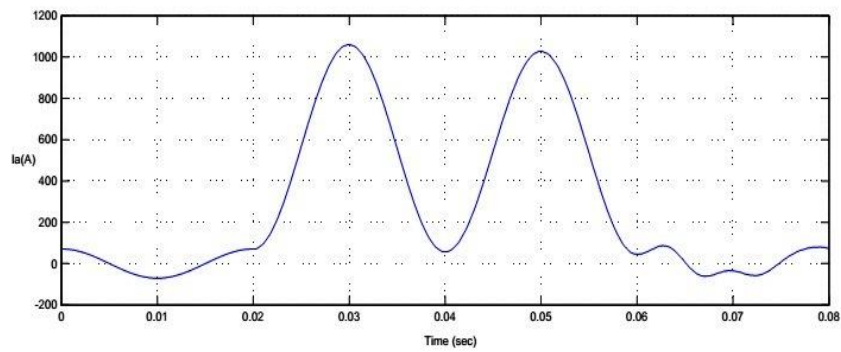


Fig. 11. Line current waveforms with measurement at terminal S.

Fig. 12. Line current waveforms with measurement at terminal R.

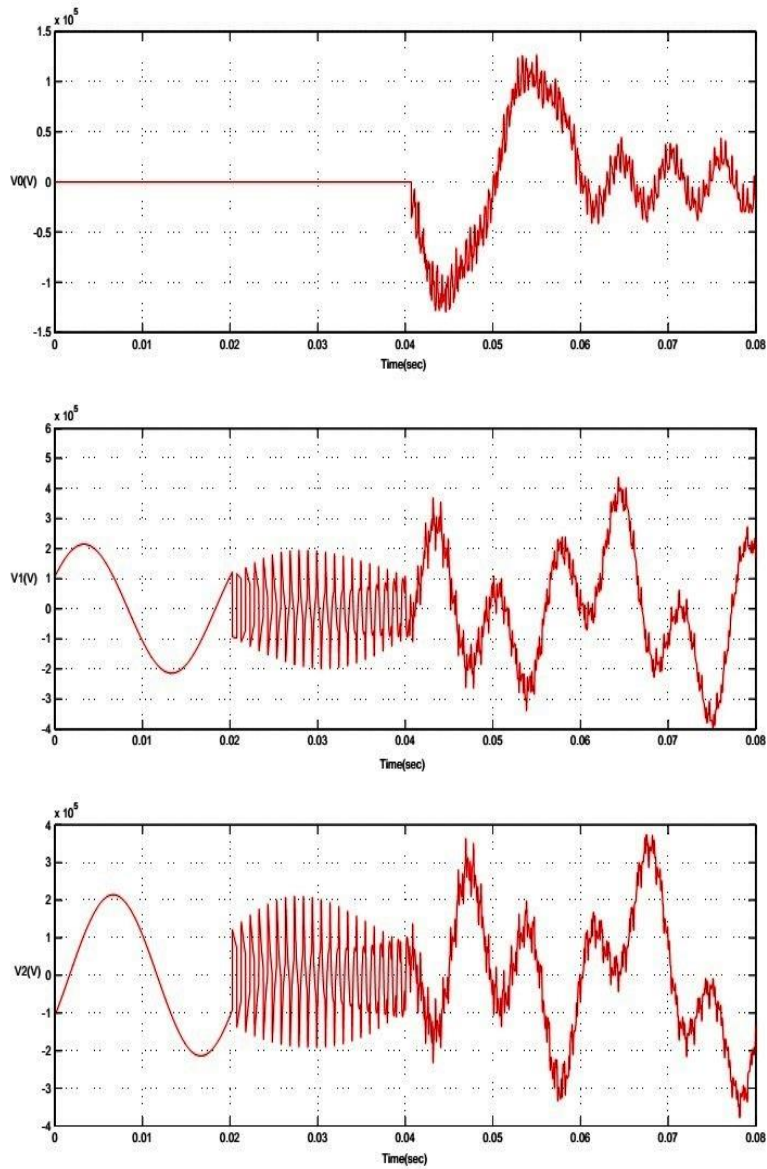


Fig. 13. Three-phase voltage waveforms in modal domain for terminal S.

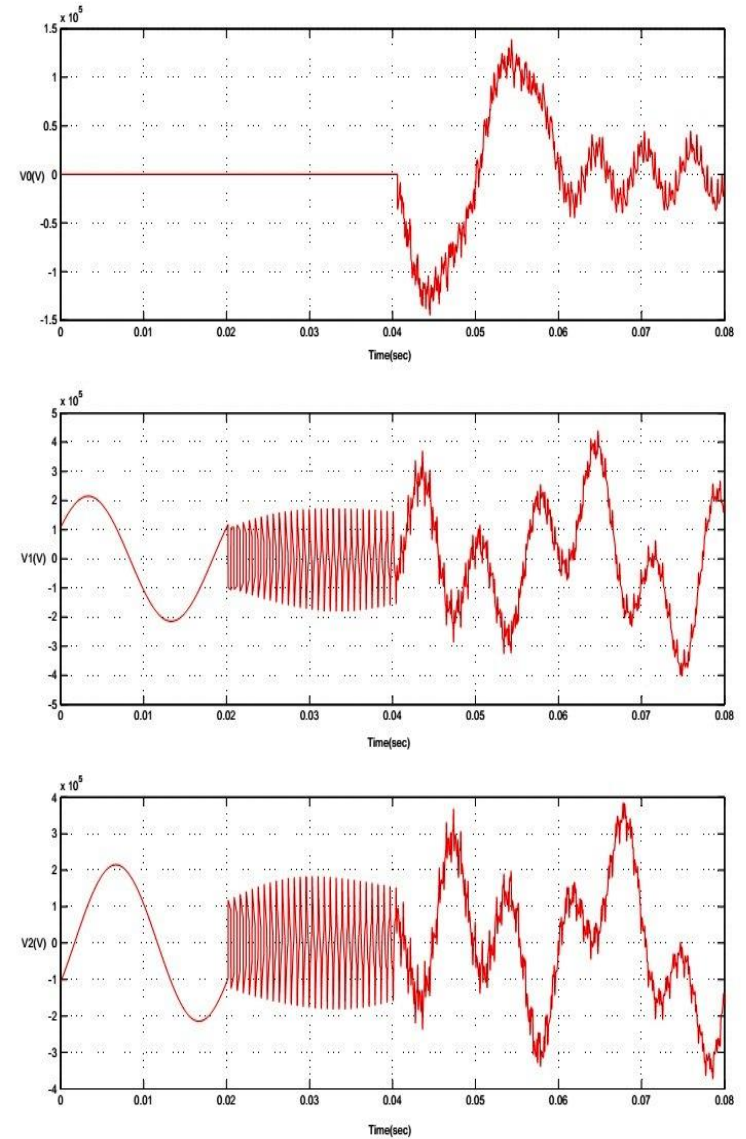


Fig. 14. Three-phase voltage waveforms in modal domain for terminal R.

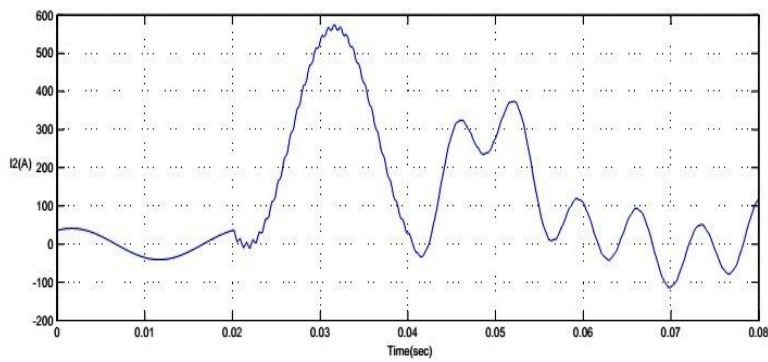
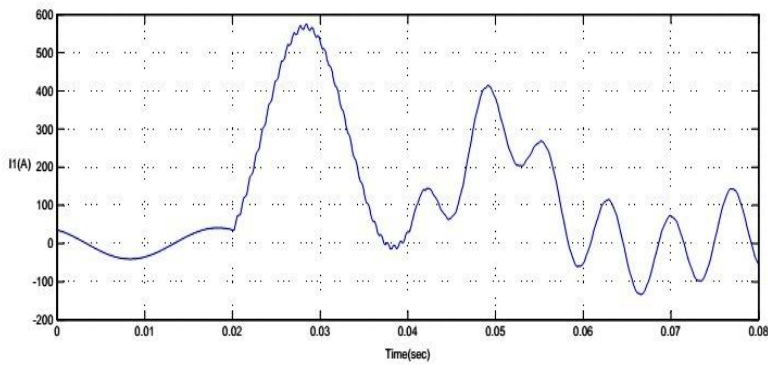
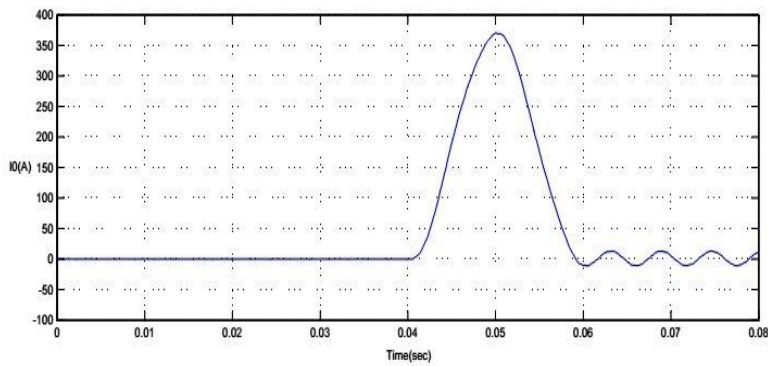


Fig. 15. Line current waveforms in modal domain with measurement at terminal S.

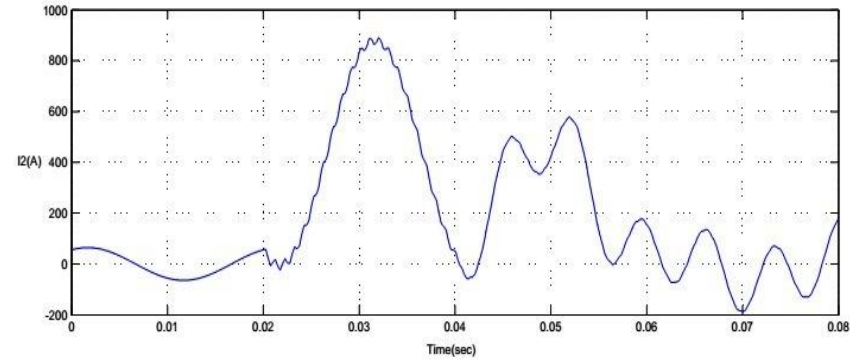
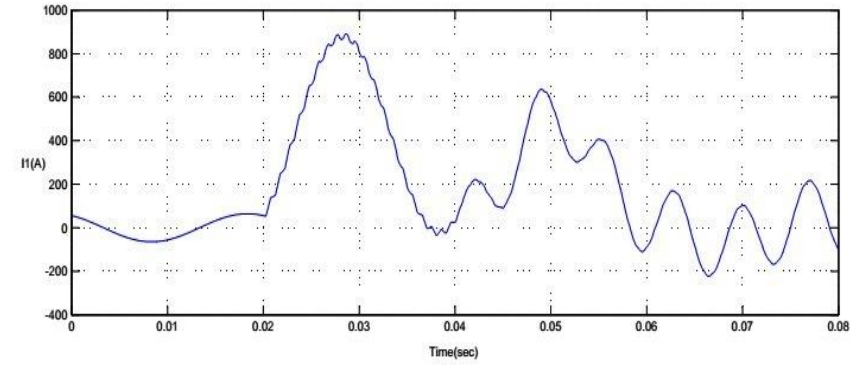
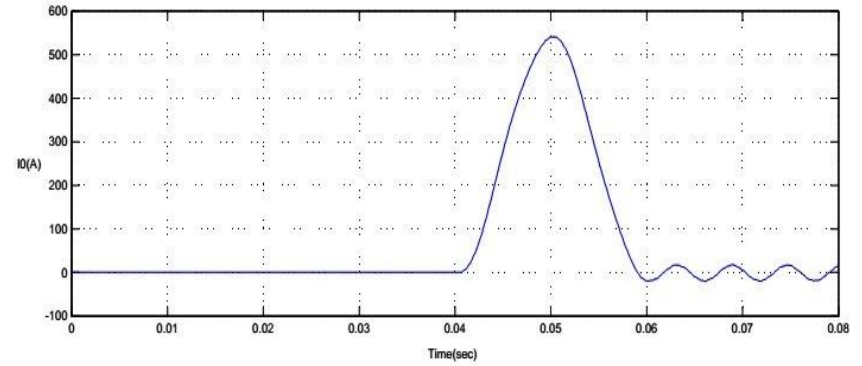


Fig. 16. Line current waveforms in modal domain with measurement at terminal R

TABLE II

ATTAINED SOLUTIONS FOR WOA AT DIFFERENT LOCATIONS AND RESISTANCES OF FAULT =0 OHM.

Fault type	Fault real location	Fault location measured by WOA	Fault location by GWO	Error % in WOA	Error % in GWO
ABCG	5	4.9736	4.967	-0.0220	-0.0275
	50	49.4301	49.41	-0.4749	-0.4917
	100	99.937	98.9034	-0.0525	-0.9138
	115	114.906	114.831	-0.0783	-0.1408
AG	5	4.9728	4.9638	-0.0227	-0.0302
	50	49.458	49.4031	-0.4517	-0.4974
	100	99.941	98.906	-0.0492	-0.9117
	115	114.911	114.794	-0.0742	-0.1717
ABG	5	4.9731	4.9686	-0.0224	-0.0262
	50	49.461	49.4058	-0.4492	-0.4952
	100	99.954	98.886	-0.0383	-0.9283
	115	114.908	114.842	-0.0767	-0.1317
AB	5	4.9801	4.973	-0.0166	-0.0225
	50	49.851	49.7056	-0.1242	-0.2453
	100	99.952	98.9171	-0.0400	-0.9024
	115	114.941	114.889	-0.0492	-0.0925

TABLE III

ATTAINED SOLUTIONS FOR WOA AT DIFFERENT LOCATIONS AND RESISTANCES OF FAULT =5 OHM.

Fault type	Fault real location	Fault location measured by WOA	Fault location by GWO	Error % in WOA	Error % in GWO
ABCG	5	5.0632	5.136	0.0527	0.1133
	50	50.487	50.497	0.4058	0.4142
	100	99.799	99.698	-0.1675	-0.2517
	115	115.207	115.226	0.1725	0.1883
AG	5	5.2005	5.290	0.1671	0.2417
	50	50.307	50.474	0.2558	0.3950
	100	99.834	99.588	-0.1383	-0.3433
	115	115.709	115.798	0.5908	0.6650
ABG	5	5.1837	5.1989	0.1531	0.1658
	50	50.615	50.863	0.5125	0.7192
	100	99.981	98.895	-0.0158	-0.9208
	115	115.967	115.981	0.8058	0.8175
AB	5	4.951	4.869	-0.0408	-0.1092
	50	50.361	50.6101	0.3008	0.5084
	100	100.83	100.977	0.6917	0.8142
	115	114.583	114.497	-0.3475	-0.4192

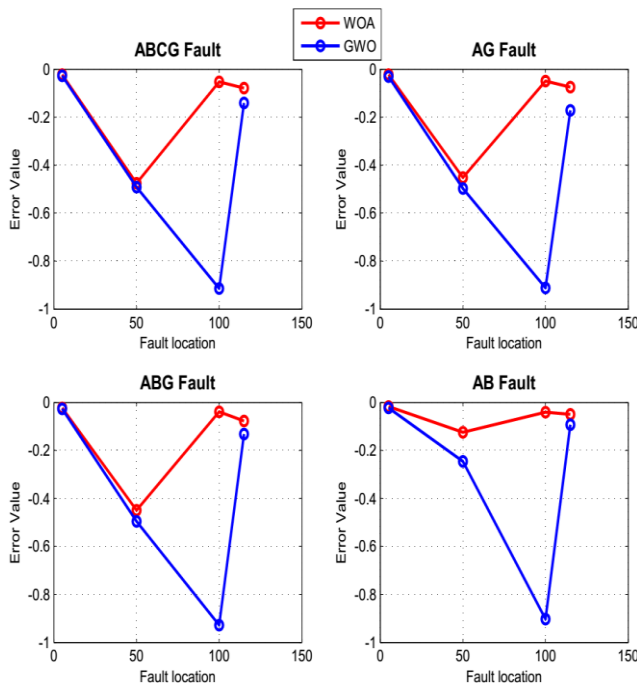


Fig. 17. Error profile at different fault location with resistance of fault =0 ohm.

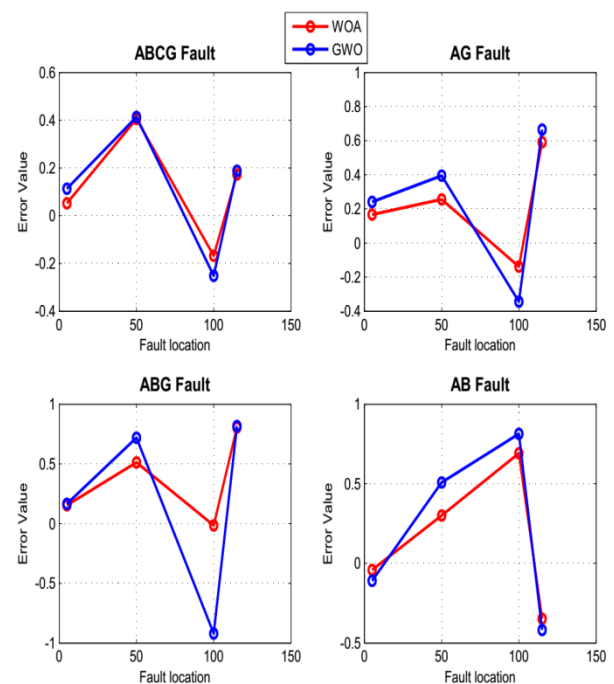


Fig. 18. Error profile at different fault location with resistance of fault =5 ohm.

TABLE IV

ATTAINED SOLUTIONS FOR WOA AT DIFFERENT LOCATIONS AND RESISTANCES OF FAULT =15 OHM.

Fault type	Fault real location	Fault measured location by WOA	Fault measured location by GWO	Error % in WOA	Error % in GWO
ABCG	5	5.2641	5.2798	0.2201	0.2332
	50	50.135	50.261	0.1125	0.2175
	100	99.893	99.6029	-0.0892	-0.3309
	115	115.14	115.301	0.1167	0.2508
AG	5	5.0370	5.1470	0.0308	0.1225
	50	50.218	50.4011	0.1817	0.3342
	100	100.063	100.264	0.0525	0.2200
	115	115.271	115.740	0.2258	0.6167
ABG	5	5.1837	5.1989	0.1531	0.1658
	50	50.615	50.863	0.5125	0.7192
	100	99.981	98.795	-0.0158	-1.0042
	115	115.567	115.605	0.4725	0.5042
AB	5	4.6821	4.3979	-0.2649	-0.5018
	50	50.539	50.581	0.4492	0.4842
	100	100.795	100.890	0.6625	0.7417
	115	114.476	114.364	-0.4367	-0.5300

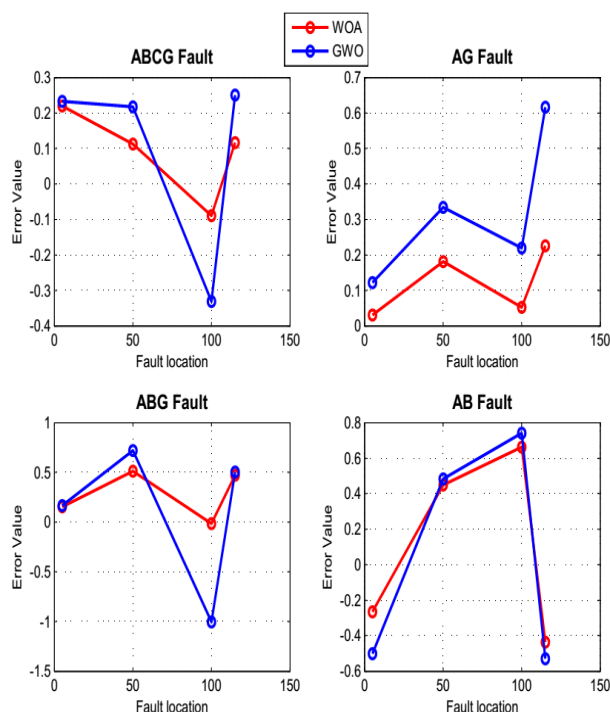


Fig. 19. Error profile at different fault locations with resistance of fault =15 ohm.

Tables II-IV show the comparison between the WOA and GWO algorithms. Based on different locations and fault resistance, the results of all fault types are illustrated in these tables. It is clear that WOA and GWO show the results accurately in spite of the fault type and fault resistance.

Figs. 17-19 show the error profile of the used algorithms at different fault locations. The analysis revealed a strong capability of the proposed approach (%error<1). It can be seen that the WOA algorithm has a higher capability than the other one. Also, Figs. 20-23 illustrate the effect of fault resistance on error value in different fault locations. As is shown, the fault resistance affects detection accuracy and %error. Although it is true for all fault types wherever the fault is, fault location is detected with minimal error values. The same has been included in Tables I-IV.

VII. CONCLUSIONS

A new correct fault location algorithm was used to compute the correct location of fault based on the Bergeron model of transmission line. In order to clarify the idea about the proposed method used in this paper, some factors such as simulation time, number of inputs, and rules are considered. Based on these factors, the complexity level is determined. In this article, some simulations were performed in different conditions, and the performance of the proposed method was compared with the GWO method. The aforesaid conditions are as follows: symmetrical and unsymmetrical faults, different fault locations, and different fault resistance. The results indicated the superiority of the proposed method in all cases. The main advantages of the proposed method are as follows:

- High accuracy of calculations
- High operating speed and low computational time
- Suitable to search for the solutions
- Low complexity of implementation
- Correct operation in different conditions of fault

Based on these advantages, the concerns on utilities about the service interruptions and down times are minimized by the proposed method. In this work, it is supposed that the location of PMU is known. In future works, the allocation of PMUs is recommended in the process of the problem definition.

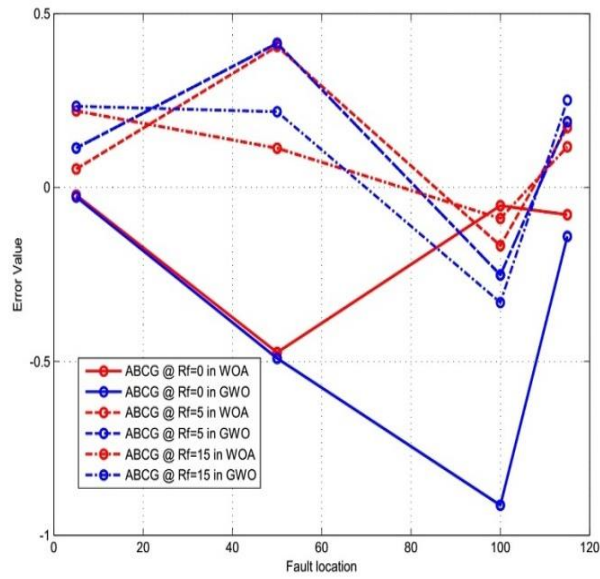


Fig. 20.Error value at different fault resistance for ABCG fault

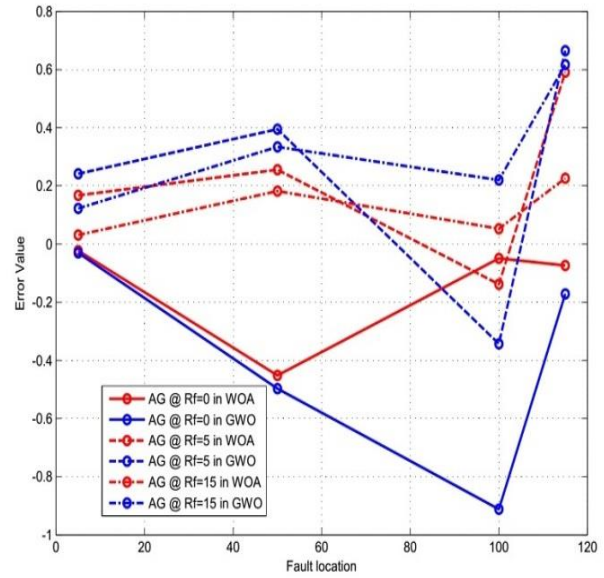


Fig. 21.Error value at different fault resistance for AG fault

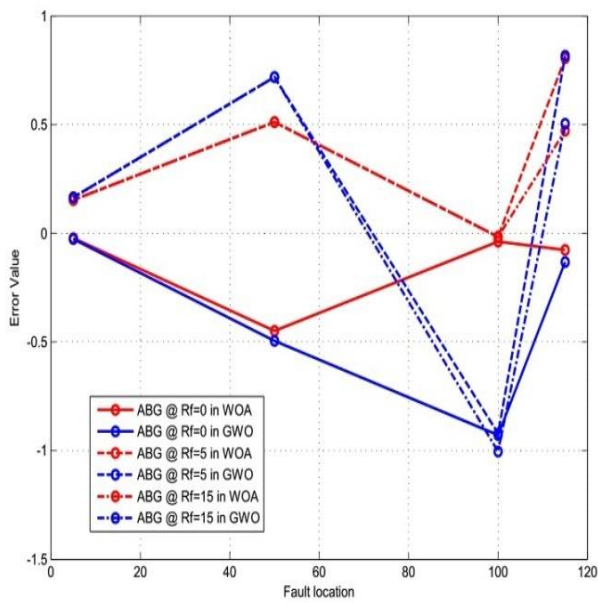


Fig. 22.Error value at different fault resistance for ABG fault.

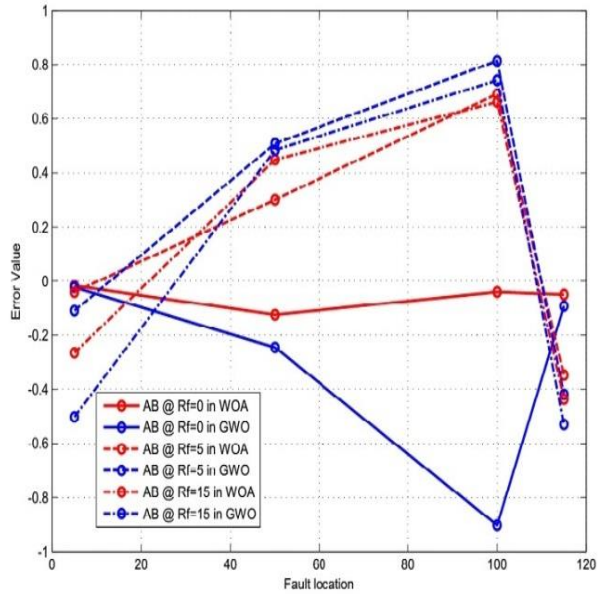


Fig. 23.Error value at different fault resistance for AB fault.

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