Coordination of Directional Overcurrent Relay Characteristics Using the PSO Optimization Algorithm

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Abstract-- **This article discusses the coordination of directional overcurrent relays (DOCRs) in the power system transmission lines. In these relays, four characteristics are used as variables to calculate coordination between them. These variables include PS, TMS, A, and B, which are used to obtain optimal coordination between relays. In this article, two fault locations are considered to obtain optimal coordination. One of them is near the relay (at the 10%-line beginning) and another is fault far from the relay (at the 90%-line end). The problem of coordination of relays is solved and optimized using the PSO optimization algorithm. The proposed method has been tested in the standard distribution 6-Bus IEEE system and its results are stated. The results of the PSO optimization method that was obtained have been compared with traditional methods such as GA-NLP. Comparing the results of this method with the traditional methods presented in the other articles, we found that the presented method obtains more optimal results than other traditional methods. Since the proposed method minimizes the operation time of DOCRs relays. This method is a reliable and effective method for calculating coordination between relays.**

Index Terms-- **Directional Overcurrent Relays (DOCRs), Coordination, PSO Algorithm, 6-Bus IEEE System, TMS, PS, Coordination Time Interval (CTI), Primary and Backup Relay, Near and Far from Relay Fault, GA-NLP**

I. INTRODUCTION

IN order to have a reliable power system, we must have correct relay coordination. Proper relay coordination works in such a way that it simply disconnects the faulty part from the system and keeps the healthy part working [1]. This means that in the event of a fault, the maximum utilization of the power system can be made and the minimum failure (only the damaged part) occurs [2,3]. To increase the efficiency of the power system, there should be a minimum amount of interruption (minimum time interval) between primary relays and backup relays. Also, the main relay must disconnect the faulty part from the network in the shortest possible time [4]. As a result, proper coordination between the relays is an essential requirement for a reliable system. Relays with inverse time characteristics (IDMT) are used in power systems frequently. Directed over current relays (DOCRs) due to their low price, high efficiency, and high effectiveness are suitable choices for basic protection. Relays with optimal settings should be used to increase coordination between relays [5]. Older relays, such as electromechanical relays, have low sensitivity and also require more maintenance. As a result, numerical relays are used today.

Numerical relays have more advantages than electromechanical relays. Among them are high flexibility, simplicity of communication with other equipment such as CT, PT, GPS, fault information storage, adaptive relays, self-checking equipment, high reliability, and safety against changing parameters. In the past, a lot of research has been done on the coordination between relays [6]. Of course, coordination between relays is described by parameters such as TMS and PS [4,7]. Meanwhile, in some research, the operation time of backup relays has been studied as well as the main relays [8,9]. Many relay manufacturers include for relay options that allow the user to select a characteristic of the relay. In reference [8,10], piecewise linear characteristic is used for the characteristic of numerical relays. Many papers have discussed the coordination analysis of relays for transmission line mid-fault [7,11]. Of course, some articles have also discussed the near fault and far from fault toward the main relay [12-14]. The possibility of a fault occurring in a line depends on its length, and there is a possibility of a fault occurring at any distance from the relay. This article introduces how to improve coordination between directed over current relays (DOCRs). The location of the faults is determined at two points. The first point is near the relay (at the 10%-line beginning) and the second is very far from the relay (at the 90%-line end). The considered relay which is intended for coordination studies between relays, is the inverse characteristic time (IDMT) relay. The speed of the relay against the maximum fault current and the sensitivity of the relay against the minimum fault current should be checked. Our innovation is the use of the PSO method to improve coordination between inverse characteristic time relays (IDMT), for faults near and far from the relays. In these relays, 4 characteristics include PS, TMS, A, and B are used as variables to calculate coordination between them. To find the optimal characteristics, we used from PSO optimization method. Results show that PSO is a very suitable method to get the optimal solution. The high speed to find the optimal characteristic in this method is one of the advantages of the PSO algorithm. In this method, at the specified time, the results are more optimal than other methods (GA, NLP, and GA-NLP) [1,11]. Also obtained characteristics are flexible and optimal

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and compared to the traditional method operation, operation time is lower.

In this article, optimal values of four variables including TMS, PS, A, and B for each relay have been obtained. The proposed method has been tested in the standard distribution 6-Bus IEEE system [1]. Also, the value of the objective function and the number of repetitions of the proposed method are lower than the values of other methods (like GA-NLP method [1]). Meanwhile, this method found a minimum amount minimum time interval (CTI) and also disconnects faulty part, in the shortest possible time. As a result, the efficiency and reliability of the power system will be increased.

In continuing described sections of this research. The relay coordination problem is discussed in section II. The proposed coordination method and optimization method are also explained in sections III and IV. Its results are also checked in the 6-Bus IEEE System and discussed in section V.

II. FORMULATE THE PROBLEM

The important issue in the coordination of traditional directed over current relays (DOCRs) relays is to find the summation of the operation time of the relays. The relay operation time is a function of two characteristics or variables: TMS & PS. According to the IEC60255 standard [15], the operation time of the T_{OP} relay is expressed as follows:

$$T_{OP} = \frac{A * TMS}{(\frac{I_{SC.3ph}}{I_{Pickup}})^{B} - 1} \quad (1)$$

Parameters A and B are constant coefficients whose values are different for all types of overcurrent relays. $I_{SC.3ph}$ It is the three-phase short-circuit current that the relay sees at the CT secondary. Also I_{Pickup} is the minimum amount of current at which the relay starts to operate. It is expressed as follows [1]:

$$I_{Pickup} = PS * \ CT_{Sec\ Rated} \quad (2)$$

$CT_{Sec\ Rated}$ is the nominal value of CT output current.

In this article, the total operation time of the relays is an objective function. Of course, in this objective function (relay coordination problem) for both faults near the relay (at the 10%-line beginning) and far from the relay (at the 90%-line end), the operation time of the relays has been calculated. The objective function considered in this article is as follows [1]:

$$\min T = \sum_{j=1}^{M} \left(\sum_{i=1}^{NR} (t_{pij} + \sum t_{bij}) + \sum_{i=1}^{FR} (t_{pij} + \sum t_{bij}) \right) \quad (3)$$

In this equation, *M* is the total number of relays in the system. *NR* is the total number of near relay faults (at the 10%-line beginning) And *FR* is the total number of faults away from the relay (at the 90%-line end).

For the *i-th* fault location of the and *j-th* relay main and backup relay operation times are t_{pij} and t_{bij} , respectively.

To obtain optimal coordination between relays, four variables TMS, PS, A, and B are considered. In the problem of coordination between relays in a system that includes N relays, 4 x N variables are considered.

$$[x_1 \ldots. x_N], [x_{N+1} \ldots. x_{2N}], [x_{2N+1} \ldots. x_{3N}], [x_{3N+1} \ldots. x_{4N}] \quad (4)$$

As in Fig. 1, for relay R3, faults f_1 and f_2 are known as faults near the main relay and faults far from the main relay [16,17].

For optimization, four characteristics of each relay are used as variables. The variables include TMS, PS, A, and B. Finally, by using these variables, the objective function is optimized. The optimization constraints are stated as follows.

A. Limitation of TMS Value

For effective and reliable protection, the main relay must operate at a specified time that is introduced by operators. The maximum time delay should be 4.0 seconds and the minimum time should be greater than the predefined time of 0.1 seconds [18].

$$t_{i,k\ min} \leq t_{i,k} \leq t_{i,k\ max} \quad (5)$$

$t_{i,k\ max}$ & $t_{i,k\ min}$ are the maximum and minimum operation times of the relay in the *i-th* location and the *k-th* protection zone.

Also, the maximum and minimum values for TMS are considered as follows:

$$TMS_{i,k\ min} \leq TMS_{i,k} \leq TMS_{i,k\ max} \quad (6)$$

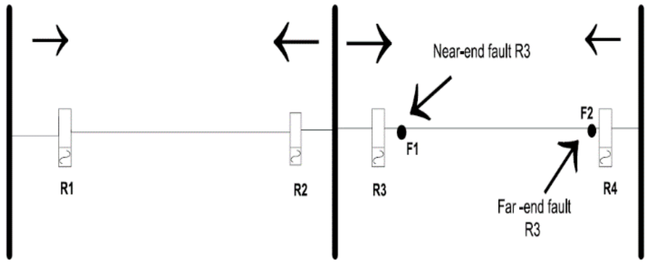

Fig. 1. Near fault and far from fault points toward relay R3 [16,17]

The minimum and maximum values of TMS at each *i-th* location are considered in the range [0.025 - 2].

B. Coordination Time Interval Limit (CTI)

If the primary relay fails to separate the faulted part from the system within the specified time, the backup relay must clear the fault. The time difference between the main relay and the backup relay is called the coordination time interval (CTI) [19].

$$t_{bi,k} - t_{i,k} \geq \Delta t$$

$t_{i,k}$ is the operation time of the *i-th* main relay, and $t_{bi,k}$ is the operation time of the backup relay for fault in the *k-th* Location of the feeder. Δt is the minimum value of *CTI* time, which is equal to 0.2 seconds according to [20]. For the studied system, the number of main-backup relay pairs is equal to 64.

C. Limiting the PS Value

The PS value of DOCR relays is considered one of the variables of the coordination problem in the studied system. For this variable in the coordination problem of relays, the upper and lower limits are included. The range of PS is defined as:

$$PS_{min} \leq PS \leq PS_{max} \quad (7)$$

PS_{min} and PS_{max} are the upper and lower limits of PS. They are considered in the range [0.5-2.5].

D. Continuous Variables A and B

In traditional methods, A and B are constant values obtained from the characteristic curve of the DOCR relay. But in the method presented in this case study system and reference [1], relays A and B are variable in the problem of coordination. The optimal values of these variables are obtained by determining the upper and lower limit values in the problem. The upper and lower limits of the two variables A and B are obtained from the fixed values that exist in the characteristics of traditional relays.

In this case study system, the minimum and maximum values for the continuous variables A and B are specified. The range of changes of A in this article is included in [0.14-80] and the range of changes of B is in the range of [0.02-2]. To solve the problem of coordination of relays, the minimum and maximum values of the variables are modeled as follows:

$$[A^{LB1}, TMS^{LB1}, PS^{LB1}, B^{LB1}, \dots, A^{LBN}, TMS^{LBN}, PS^{LBN}, B^{LBN}]$$
$$[A^{UB1}, TMS^{UB1}, PS^{UB1}, B^{UB1}, \dots, A^{UBN}, TMS^{UBN}, PS^{UBN}, B^{UBN}] \tag{8}$$

LB/UB There are minimum and maximum values of the variables for the *N-th* relay.

III. PROPOSED PROTECTION COORDINATION METHOD PROBLEM

This method is a baseline activity based on real-time settings that makes the DOCR relays not malfunction [21,22]. Because of dynamic changes in the system such as changes in the fault current with time, steps of these methods are necessary.

In addition, in the relay settings, we need real-time settings to obtain the minimum relay operation time and maintain the minimum coordination time requirement at the same time. To update the relay settings according to changes in the system conditions, it is necessary to properly connect the field equipment with the relay [23,24].

In this method, real-time system information such as current, load, voltage, circuit breaker status, and power plant production are needed. Each relay in the system is marked with its IP address to record real-time data changes. For each event in the network, the fault current is recalculated. Additionally, for the new fault current, the existing relay settings are checked for protection coordination. If there is any mismatch, the relay settings are recalculated and updated.

The settings of DOCR relays can be updated online using information obtained from field equipment such as intelligent electronic equipment (IED). TCP/IP communication protocol is required to complete this map. The appropriate reverse current-time characteristic must be selected for numerical DOCR relays. Meanwhile, a fast, robust, high-efficiency processor is required in the central protection center (CPC) to search for adaptive relay coordination. Updated settings and proper reverse time characteristics are loaded on all DOCR relays from numerical, of course, from the central protection center (CPC). The settings before this loading as well as the previous characteristics of these relays are deleted from the DOCR memory. This research is focused on the calculation of relay settings in different system conditions [1].

IV. PROPOSED PSO METHOD

The PSO optimization algorithm has been used to obtain optimal relay coordination of the case study system. The main advantages of PSO are the achievement global optimal solution and does not fall into the local optimal trap. The advantage of the GA optimization method is the searching in a large solution space. However, there are some problems with the GA method, such as not converging to the optimal solution. Of course, this problem does not exist in the PSO method, and the accuracy speed of the PSO algorithm is higher than other optimization methods such as GA and GA-NLP. In this research by using the PSO algorithm, optimal values for the variables TMS, PS, A, and B are obtained for all relays in the 6-Bus IEEE system. Time constraints and coordination constraints are combined in the optimization tool in a suitable ratio. The upper and lower limits of TMS, PS, A, and B variables are specified in the programming algorithm. Finally, the optimal solution is obtained using two-time objective functions and coordination of relays using the PSO method. The algorithm finally obtains an optimal solution. The values obtained from this algorithm are global optimal values.

V. DISCUSSIONS AND RESULTS

The protection proposed method provided for the coordination of numerical DOCR relays based on characteristics has been tested in a 6-Bus IEEE system. This system's features are described in the bottom section.

A. The 6-Bus IEEE Test System

As Fig. 2 this system includes 3 generators that are connected to buses 1, 2, and 3. It also consists of 22 numerical DOCRs along with 64 combinations of main-backup relay pairs [1].

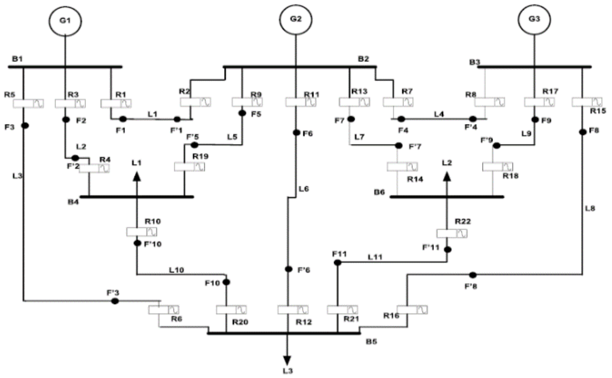

Fig. 2. The 6-Bus IEEE Distribution system [1]

11 numbers of faults near the relay, in the first of the line length, by the following names are shown:

$$f_1 \cdots f_{11} \tag{9}$$

Also, 11 numbers faults far from the relay, at the end of the line length, which are shown with the following names:

$$f_1' \cdots f_{11}' \tag{10}$$

Also, according to Fig. 2, For the line between buses B1, and B2, the f_1 fault point is used as a near point fault for the R1 relay and as a far fault point for the R2 relay. f_1' fault is used as a near point fault for the R2 relay and as a far fault point for the R1 relay.

For the given 6-Bus IEEE System, the Characteristics of the system are in Table I [25].

TABLE I
Characteristics of the 6-Bus IEEE System [25]

System Quantities	Valves
Generator G1, G2, and G3	6.3 KV,6 MVA,X'_d=0.2 p. u
Load at Buses B4, B5, and B6	2.4 MVA, 0.9 pf
Line Impedance	0.08+j0.16 Ω/km (all lines are 500 m long)

Also, for all 6-Bus IEEE system relays, CT data are required. The number of numerical relays in this system is 22 and the ratios of CTs are Listed in Table II [1].

TABLE II
CT Ratio of All Relays of the 6-Bus IEEE System [1]

Relay No.	CT Ratio	Relay No.	CT Ratio
R1	1200/5	R12	1200/5
R2	1200/5	R13	800/5
R3	1200/5	R14	400/5
R4	1000/5	R15	400/5
R5	800/5	R16	400/5
R6	600/5	R17	1000/5
R7	800/5	R18	500/5
R8	400/5	R19	300/5
R9	1600/5	R20	300/5
R10	1000/5	R21	400/5
R11	600/5	R22	300/5

In Table III, all fault currents seen by all relays in the 6-Bus IEEE System are shown [1].

TABLE III
Fault Currents are seen by All Relays of the 6-Bus IEEE System [1]

Fault Location	Primary Relay		Backup Relay	
	PR1	PR2	BU1	BU2
F1	R1 (4126)	R2 (4298)	R4, R6	R8, R10, R12, R14
F2	R3 (4367)	R4 (3389)	R2, R6	R9, R20
F3	R5 (3012)	R6 (2416)	R2, R4	R11, R15, R19, R22
F4	R7 (2391)	R8 (1312)	R1, R10, R12, R14	R16, R18
F5	R9 (5527)	R10 (3372)	R1, R8, R12, R14	R3, R20
F6	R11 (1956)	R12 (1701)	R1, R8, R10, R14	R5, R15, R19, R22
F7	R13 (2827)	R14 (1362)	R1, R8, R10, R12	R17, R21
F8	R15 (1124)	R16 (1604)	R7, R18	R5, R11, R19, R22
F9	R17 (1388)	R18 (1795)	R7, R16	R13, R21
F10	R19 (1204)	R20 (1098)	R3, R9	R5, R11, R15, R22
F11	R21 (1559)	R22 (1096)	R5, R11, R15, R19	R13, R17

This table describes the fault currents seen by relays in two places, the faults near relays and the faults far from relays. For example, if the F1 fault location is near the R1 relay, the near fault current seen by the R1 relay is 4126 A. Also, far from the fault current seen by the R1 relay is 4298 A. If F1 fault location is near the R2 relay, the fault current seen by R2 relay is 4298 A. Also, far from fault current seen by the R2 relay is 4126 A. As shown in Table III, the R4 and R6 relays are backup protection for the R1 relay. Also, the R8, R10, R12, and R14 relays are backup protection for relay R2.

B. Comparison between PSO and Traditional Methods

The values of the objective functions have been calculated using the proposed method. The optimal coordination of DOCR has converged in *33* iterations and the value of the objective function is equal to *6.9005*. The value of the objective function obtained in the proposed method has been compared with the values obtained in other researches. As can be seen, the number of repetitions as well as the value of the objective function, is lower than the GA-NLP method [1] and other methods. According to the obtained results, the value obtained in this method has convergence to a lower optimal value than traditional methods [1].

As shown in Table IV, the performance time of the proposed optimization method is lower than the traditional methods.

TABLE IV
Comparison between PSO and GA-NLP Optimization Technique for the 6-Bus IEEE System

Optimization Method	GA-NLP	PSO
Approach Objective Function	8.67148	6.9005
Simulation Time (s)	13.41	4.024
No. of Iterations	44	33

Also, this table shows that the value of the objective function and the number of iterations of the PSO optimization method are lower than the traditional methods.

In Table V, the CTI values at the proposed method and the traditional methods are compared. It shows that the values obtained from this article are lower than the traditional methods values [1].

TABLE V

CTI Using GA-NLP and PSO Approach for the 6-Bus IEEE System

GA-NLP Optimization Value of CTI	Obtained Value	PSO Optimization Value of CTI	Obtained Value
Maximum	4	Maximum	0.94345
Minimum	0.2	Minimum	0.01252
Average	1.246	Average	0.19819

As a result, in Table V, the operation time of the backup relay, which is the sum of the operation time of the main relay and coordination time interval (CTI), is lower than previous methods. These results are obtained for 64 main-backup relay pairs, clearly showing that the coordination of relays in the proposed method is higher than other methods presented in previous articles. The results show that the proposed simulation is a strong and effective method to obtain optimal coordination between relays. Obviously, for any fault condition, the main relay must operate within the specified time to disconnect the faulted section from the system. But if the main relay does not work after a specific time, the corresponding backup relay should work. Finally, it should be noted that the optimal values calculated in this article are global optimal points and the presented method greatly improves the operation time of the relays and the optimal coordination between the relays.

C. *Final Results*

As shown in Table VI the optimal values of 4 variables including TMS, PS, A, and B for each relay, have been obtained by using the PSO optimization method. Finally, the obtained results are compared with the traditional methods [1]. The objective functions considered for this research are the total operation time of the relays and the coordination time interval (CTI).

TABLE VI

Optimized Setting Using a Proposed Strategy for the 6-Bus IEEE System

Relay NO.	PSO			
	A	TMS	PS	B
R1	13	0.3	0.5	1.8
R2	15	0.4	0.6	2
R3	14	0.1	1.8	1.9
R4	16	0.3	1.2	1.8
R5	17	0.4	0.5	1.7
R6	20	0.4	0.5	1.9
R7	44	0.1	1.5	2
R8	20	0.1	1.3	1.9
R9	21	0.1	1.5	1.8
R10	22	0.3	1.2	1.8
R11	20	0.1	1.8	1.7
R12	22	0.2	0.5	1.9
R13	23	0.3	0.5	2
R14	50	0.1	0.8	2
R15	25	0.1	1.4	1.8
R16	23	0.2	2	1.7
R17	20	0.1	0.5	1.8
R18	21	0.1	2	2
R19	22	0.4	0.5	1.9
R20	24	0.2	1.5	1.9
R21	24	0.4	1.4	1.8
R22	24	0.2	1.8	2

Fig. 3 shows the convergence diagram of the 6-Bus IEEE System obtained using the PSO optimization algorithm. Fig. 3 shows that the PSO method convergence speed is very high. Also, the iteration number of objective function value convergence is lower than in other methods [1]. In the 6-Bus IEEE System there are 64 pairs of the primary backup relays. The primary of these pair's relay operating time, is shown in Fig. 4. This picture shows the amount of operation time the primary of the primary-backup relay pair. As introduced, to improve coordination between relays, reduce the amount of operation time of the power system primary relays. This picture shows that the operation time of power system primary relays is lower than other traditional methods. This result is achieved by the PSO optimization method.

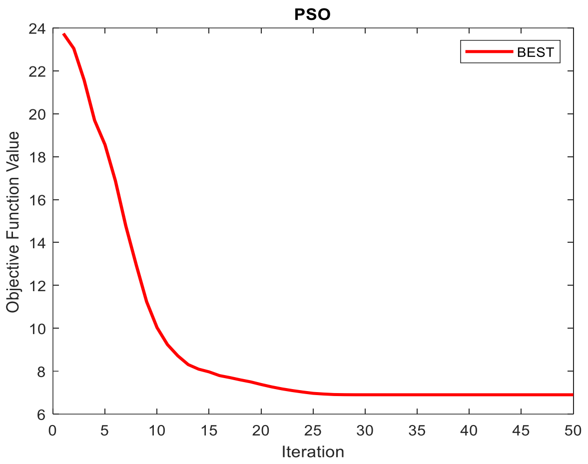

Fig. 3. Convergence curve using PSO optimization method for the 6-Bus IEEE system

The secondary pair of primary-backup relay operating time is shown in Fig. 5. This picture shows the limit of operation time for backup of the primary-backup relay pair.

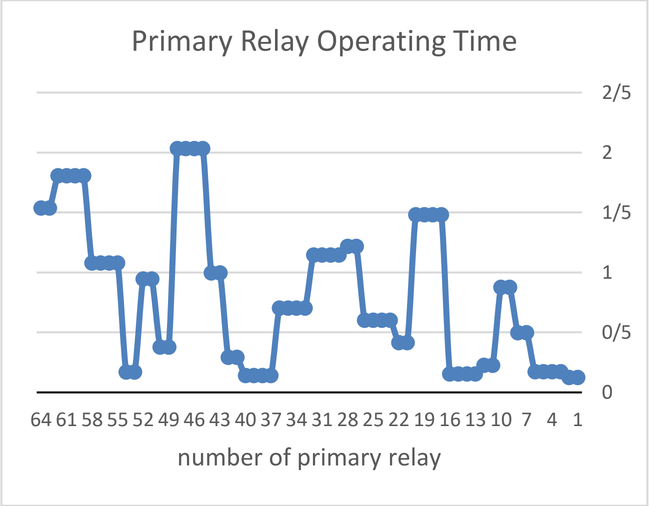

Fig. 4. Primary relay operating time for the PSO optimization method in the 6-Bus IEEE system

As introduced, to improve coordination between relays, reduce the amount of operation time of the power system backup relays. This picture shows that the operation time of power system backup relays is lower than other traditional methods. This result is achieved by the PSO optimization method.

The difference between backup and primary time operation is the coordination time interval (CTI). As introduced to improve coordination between relays, the main purpose is to reduce the amount of coordination time interval (CTI) of power system relays. This picture shows that the coordination time interval (CTI) of power system relays is lower than other traditional methods. If the amount of CTI is lower, the coordination of relays is better. Fig. 6 shows the CTI of the primary backup relay pair of the 6-Bus IEEE System. This result is achieved by the PSO optimization method.

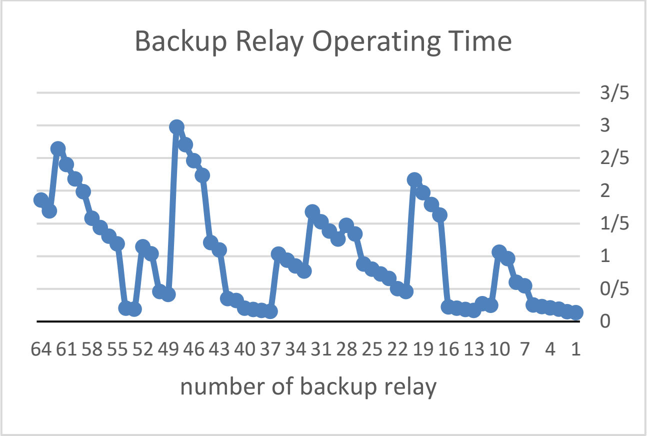

Fig. 5. Backup relay operating time for the PSO optimization method in the 6-Bus IEEE system

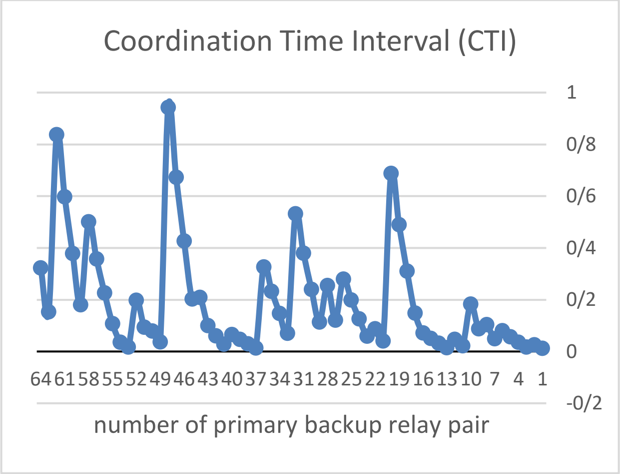

Fig. 6. CTI of primary backup pair relay for the PSO optimization method in the 6-Bus IEEE system

VI. CONCLUSION

The purpose of this paper is to present an adaptive coordination method between directional overcurrent relays (DOCRs) in the power transmission lines. This approach is intended for the location of faults near the relay (at the 10%-line beginning) and far from the relay (at the 90%-line end) in a transmission line. In this article, which has studied numerical relays, four variables have been considered to optimize the relay coordination problem. These 4 variables include PS, TMS, A, and B. This study was performed on the 6-Bus IEEE system and its results are also stated. The method used for optimization on the 6-Bus IEEE System is the PSO optimization algorithm. This optimization method is one of the fastest and best optimization methods compared to other methods. The results of this method, which has been performed in the 6-Bus IEEE system, have been compared with the results of traditional methods such as GA-NLP. Comparing the results of this method with traditional methods such as GA-NLP shows that the results of the PSO method are more optimal and the coordination between relays is better. Results of the coordination discussion of relays, show that the method presented in this article is much more effective and useful in managing and controlling the coordination of relays.

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